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THESIS

MAGNETIC INDUCTIVE SENSOR APPLICATIONS FOR ROBOTIC ORDNANCE DETECTION AND RECOVERY

by

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December, 1995

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MAGNETIC INDUCTIVE SENSOR APPLICATIONS FOR ROBOTIC ORDNANCE DETECTION AND RECOVERY

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ABSTRACT

The use of robotic vehicles to detect and remove unexploded ordnance (UXO) from battlefields and training ranges is currently being explored by the Naval Explosive Ordnance Disposal Technical Division, Indian Head, Maryland. In support of this effort, research was conducted in the characterization and use of small, commercially available magnetic inductance sensors to detect a variety of common U.S. submunitions. Sensor test bed mounting on a small wheeled vehicle with sweep device allowed for dynamic testing against submunitions under laboratory and field conditions.

TABLE OF CONTENTS

LIST OF FIGURES

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I. INTRODUCTION

A. BACKGROUND

Wherever man has waged war, or tested the implements of war, the remnants of the weapons which he used have remained. While the corroded swords of the Romans present few problems to today's population, the same cannot be said of more recent weaponry. The explosive ordnance which has been developed and used in the period since WW II has left a legacy of unexploded duds and misfires which continue to pose risks to people around the world. There is now estimated to be more than 100 million pieces of unexploded ordnance located on the earth. Most of this material is still capable of sustaining a high order detonation. The problem is, in fact, becoming worse, as technology develops cheaper and more deadly types of ordnance with longer lifecycles, while their indiscriminate use by third world countries increases. [Bartington, 1995]

Within the last thirty years, one type of newly developed ordnance has become particularly significant:the submunition. This new ordnance is peculiar for a number of reasons. First of all the submunition is small; most weigh less than a pound and can comfortably fit in a man's hand. This size allows for the packaging and delivery of large numbers of submunitions within the mother ordnance, which can be a projectile, cannister or missile. The submunition is also a durable and long-lived menace which may be encountered as either dud-fired or purposefully designed not to explode on impact. Its ability to deny target areas for general use, because of possibility of detonation, may extend for more than a decade. Their low price, tactical flexibility, and ease of delivery, have made them extremely popular. Finally, the submunition is, generally, one of the most sensitive ordnance types found in any inventory. While they can often be removed by hand, for safest treatment, they are frequently detonated in place.

The clearance of submunitions is consequently of great importance to countries, who following wars, desire to regain the safe use of agricultural land and transportation routes. It is also a concern of militaries who desire to regain the use of areas of tactical significance which submunitions have been deployed to deny. Finally, it is a consideration for those militaries and governments who are either maintaining training ranges or clearing training ranges prior to their return to civilian use. These clearance missions, one humanitarian, one military, and one a mixture of the two, are the primary focus of submunition clearance. It is important to note that the conditions under which these missions will be carried out vary substantially in regards to time, working conditions and general risk which can be tolerated.

B. CURRENT ISSUES

In the U.S. military, the task of dealing with the practical aspects of removing mis-fired or armed ordnance which poses a danger to personnel or assets belongs to Explosive Ordnance Disposal (EOD) technicians. This group is supported in its development of tactics and equipment for dealing with unexploded ordnance by the Navy EOD Technical Division, Indian Head, Maryland. The problem of submunitions clearance is, consequently, one of much interest to the NAVEODTECHDIV and programs to improve clearance safety and speed are presently underway.

In order to grasp the rationale for these projects it is important to understand the currently available techniques used to locate and dispose of submunitions. The general sensitivity of the submunition, combined with current policies desiring low fatality rates in clearance, results in exceptionally careful search techniques and disposal by remote means. The ordnance is usually located by using untrained personnel in sweep lines, supported by trained EOD technicians, which confirm and mark each ordnance as it is spotted. Following completion of the sweep, EOD technicians return to the range to place explosive countercharges to blow-in-place (BIP) remotely, or to stand off and attempt to detonate the ordnance from a distance using sniper rifles (SMUD.) In either case the clearance rates are slow, sometimes dangerous, and manpower intensive.

The problem of submunition clearance is one of tactical and humanitarian importance, and yet difficult and expensive to conduct. It is the purpose of this thesis to examine an alternative to present method of clearance, the feasibility of establishing remotely operated vehicles, in lieu of men, to accomplish submunition clearance. Work is presently underway at NAVEODTECHDIV to develop a system of radio-controlled teloperated vehicles known as RECORM to provide highly sophisticated reconnaissance and control functions in EOD range clearance scenarios. It is thought that a second, less expensive and less capable, vehicle should also be developed to provide for actual ordnance pick up and carry away (PUCA) or BIP with counter charges. This second vehicle should be inexpensive enough to allow for occasional loss due to inadvertent detonation of the ordnance, and yet sufficiently equipped to identify ordnance and conduct these planned limited operations. This thesis takes some of the first steps in examining the viability of using commercially available magnetic inductive sensors on small robotic vehicles in performing the submunition clearance mission.

C. THESIS SCOPE

The purpose of this thesis, then, is to examine a few of the issues which will directly affect the the ability of remotely operated or autonomous vehicles to conduct a limited mission of submunition clearance. The thesis is in direct support of the proposals being examined by the NAVEODTECHDIV which envision the use of combinations of reconnaissance and worker vehicles which can be deployed into an area for submunition clearance. For the purposes of this thesis, the operation is projected to take place in a non-hostile environment with few large physical obstacles to clearance. This is not a particularly artificial limitation to impose on the scenario because most submunition test and training ranges are currently maintained in particularly smooth, obstacle-free condition to allow range sweeps to be conducted without difficulty of submunition location or fear of accidental detonation. In essence, they already exist in a condition of smooth, vegetation and obstacle-free, flat surfaces. Similarly, clearance of submunitions from tactical emplacement on runways would also provide these conditions.

The thesis uses these conditions to explore possibilities for vehicle employment, submunition detection/classification by a sensor, as well as sweep system development.

D. RATIONALE

Submunition clearance is a game of odds. Many submunitions are deployed which can be picked up and carried away. This may be due to the submunition failing to arm, damage due to launch/impact or inherent insensitivity to certain movement. The ability to clear many submunitions successfully by merely carefully picking them up in the position found and carefully carrying them to a central disposal point is so well established that this process is commonly used by Marine EOD technicians (and by other services as a last resort.) There is always, however, the small chance that this movement may result in the detonation of the ordnance. The fact that this might occur on a low percentage basis is the reason why most military services recommend only blow-in-place or another remote procedure when dealing with most submunitions. It is also evident by the infrequent, but periodic, accidental death of Marine EOD technicians.

In this light, the advantage of an inexpensive autonomous robot, capable of locating and recovering submunitions, is apparent. By constructing vehicles which cost less than $500 each, and which are capable of making repeated speedy and effective sweeps of ranges, prior to the rare accidental detonation of a submunition makes this option a viable one.

E. THESIS STRUCTURE

This thesis is constructed in the following manner:

Chapter I provides introduction and background information concerning rationale for the thesis research.

Chapter II discusses current sensor technology and their applications, finally explaining the reasons for our particular sensor selection.

Chapter III provides technical information on the construction and operation of our sensor package as well as characterization of its performance in a variety of fashions.

Chapter IV discusses an optimal sweep design configuration using our sensor package, including design considerations, limitations and possible improvements.

Chapter V describes actual sweep test results using our sensor package and sweep configuration on a number of inert submunitions.

Chapter VI discusses conclusions which have been reached in this research and provides suggested direction for further study.

II. ORDNANCE SENSOR TECHNOLOGY

A. HISTORY

The detection and classification of munitions has been historically accomplished by the use of trained EOD technicians who have employed a variety of techniques. Surface ordnance was usually located quite easily by visual methods, although in some areas heavy plant growth required the use of periodic burns to increase the probability of detection. The problem of detecting buried, or submerged munitions, was another matter entirely. Initially, entire suspect areas were probed by hand, a slow and dangerous method. With the advent of rudimentary magnetic detectors such as the MK 9 Ordnance Locator, large ferrous munitions could be localized for excavation. Much non-ordnance material was located, but excavation and search efforts were streamlined. Within the last twenty years, additional advances have produced metal detectors such as the MK 26 Ordnance Locator, which are capable of sensing conductive metals of many types, and munitions of lesser size. Most of these detectors were man-carried and required substantial training in order to provide effective results.

B. CURRENT SENSOR TECHNOLOGY

Within the last decade or so, enormous advances have been made in a number of technologies which have proven to provide other alternatives in ordnance sensing. These categories of sensors can generally be divided into five groups: electromagnetic, mechanical, optical, acoustic, and exotics. New advances range from ground penetrating radars and x-ray backscatter to chemical vapor detection and bioluminescence. The majority of these technologies, however, are not easily applicable to the small robotic problem, either because the technology is still in development or because of large power/physical array requirements. The wide variety of sensors which have been developed, and even larger number made applicable to ordnance location, by dint of improvements in miniaturization and microcomputational advances, are such that there is not time or space to allow a complete discussion of them all. We will instead address the particular systems from each category which presently hold promise for use in the remotely operated vehicle/autonomous vehicle (ROV/AV) application.

1. Flux-gate Magnetometers

Utilizes the phenomenon which occurs when driving a core into and out of saturation using a magnetic field. The relative strength of the magnetic field surrounding the core can be determined by measuring the voltage spike which accompanies each transition into and out of saturation. The device measures only magnetic fields which are in existence, those fields developed by ferrous materials. This is currently the most popular type of ordnance detector being used in the field by EOD personnel. It requires a fairly large sensor array and is limited in its ability to detect only ferrous metals. [Fraden,1993]

2. Magnetorestrictive Magnetometers

A relatively new technology, it has been found that certain materials have varying resistance to electric current as the strength of the magnetic field which they are located in varies. This property has been used to build Wheatstone bridge type devices which provide accurate indications of the local magnetic field. The technology produces excellent sensitivity with low power requirements, but, as with the flux-gate magnetometer is limited to the detection of ferrous metals. [Brown, 1993]

3. Inductance Sensors

This technology is also a new development in the field of ordnance location. Using a driving magnetic field to induce eddy currents in local metals, it then detects the resultant magnetic fields or change in driver field behavior due to mutual inductance. Popular in the industrial environment for excellent range resolution, speed, and accuracy in measuring movement of machine parts, the induction sensor has found limited use in EOD technology, despite its ability to detect non-ferrous metals.[McFee, 1984]

4. Tactile Sensors

Another new technology recently developed specifically for remote/autonomous vehicle application is tactile sensing. The premise of this technology is that movement of a tactile sensor along a munition case will develop vibrations which can be analyzed using Fast Fourier

Transforms to produce characteristic signatures different from natural materials. The technology does not distinguish between ordnance/non-ordnance, or even metal/non-metal, only between natural and man-made. Current application is only to underwater use. [Mangolds,1993]

5. Optical Sensors

The use of optical sensors such as infrared, laser, or artifical sight to detect surface ordnance is currently not feasible due to large power, cost and computational requirements. Infrared variations between ordnance and background levels is a possible viable robotic option in particular climes where temperature variations are extreme, but much like artifical sight still requires larger computational capabilities than are available on the small, inexpensive robots.

C. SENSOR SELECTION

The selection of the sensor package for our use was based upon the following factors:

size- The sensor package must be physically small enough to be used by a robotic vehicle which was envisioned to be approximately 24 inches in length, 12 inches wide and 8 inches wide, roughly the size of a large remotely operated, battery-powered car.

weight- The sensor package and its power source should not weigh more than approximately four pounds, the approximate maximum payload of the test vehicle in use.

power- Optimal portable power sources available were limited to 6-30 volts DC with a current capacity of approximately 1 amp-hour. Anticipated run times of at least one hour resulted in maximum current draw of 1 ampere.

range- Original estimates of ranges required were in the tens of inches. Research showed the inability to attain these ranges while operating within the above constraints. The ability to detect submunitions of various metallic composition at ranges less than an inch was the final criteria.

sensitivity- The sensor performance with respect to detection distances was required to be radially symmetric, fairly stable, and repeatable. Sensitivity to a variety of metals was important as many submunitions are fabricated from non-ferrous metals.

adaptibility to small robotics- A rugged, cheap sensor which provided a detection output signal which was adaptable to autonomous electronic processing was required.

The sensor package chosen was the magnetic inductive sensor described in the next section. It met all of the criteria mentioned above, the most discerning of which was the ability to detect metals of a non-ferrous nature.

One additional note. The selection of this particular sensor package for the purposes of this research is not a statement of advocacy for a single sensor approach for all applications. The use of a remotely operated or autonomous vehicle for ordnance detection and classification would benefit greatly from a multi-sensor suite which incorporates a variety of sensors and uses their various signals to develop improved response. However, before moving into this advanced scenario it is required that each individual sensor system be evaluated on an individual basis. The sensor performance must be characterized based upon a variety of materials, geometries and operating conditions. Additional cost factors may also dictate a single sensor approach.

III. EXPERIMENTAL EVALUATION OF SENSORS

A. SENSOR DESCRIPTION

The sensor systems finally selected for use in this research were both inductive proximity sensors available commercially. The first system which was evaluated was a self-contained, unshielded, proximity sensor, Model ET1AN2B, manufactured by the Electro Corporation of Sarasota Florida. It is shown in Figure (1). It was powered by a DC voltage source of permissible 20-30 Volt range, and with a maximum current of 400 milliamperes. The sensor was attractive due to its rugged one-piece design and internal circuitry and self-contained LED. Unfortunately, initial tests were extremely disappointing. The sensor showed no sensitivity to detect except directly along its longitudinal axis, and ranges of detection were half an inch or less.

The second sensor system, which proved to be substantially more effective than the self contained model, was also manufactured by the Electro Corporation. This system, which included the EN401 PCB Mount Inductive Proximity Module and Model 85003 Unshielded Inductive Sense Head, required assembly of components by the user. The controller module was mounted on a circuit board with additional electrical components to maintain current draws of less than 100 milliamperes and provide desired LED and voltage signal outputs. The sensor head was also connected to the circuit board. One of the additional board components was a potentiometer which allowed adjustment of sensitivity/saturation of the system. Figure (2) provides details of the basic system wiring diagram. The power source for this system was also variable in the range 10-30 volts, but a voltage of 14 volts was chosen in order to utilize existing power supplies.

The details of the controller circuitry are not available because all of the electronics are "potted" and wiring diagrams are considered manufacturer's proprietary information. The circuit operation will be discussed in the following section.

The sensor construction is detailed in Figure (3) . The sensor head consists, basically, of a ferrite rod which has been wrapped with 33 turns, along approximately 70 per cent of its length (from the tip to the base,) with magnetic wire. A 22 kilo-ohm resistor is included in the circuit to provide more sensitivity.

B. SENSOR OPERATION

1. Theory

The sensor system operation is based upon the principle of a tuned L-C or "tank" circuit. Using the applied 14 Volts DC a driving AC frequency of approximately two volt amplitude (4 volts peak-to-peak) is produced by an electronic solid state switch and driver in the controller. The frequency chosen is such that it is near the resonant frequency of the L-C circuit which the controller and sensor have established:

$$\omega^2 = 1/LC \qquad 3.1$$

At this condition the amplitude of the voltage which the circuit experiences is at a near maximum. Figure (4) shows the relationship between frequency and voltage amplitude for this particular circuit.

The coil and ferrite core have the additional property of producing a magnetic field in the surrounding medium. If this medium contains a metal then the phenomena of induced flux linkage will occur, at least to some degree. In this case, the magnetic field will induce "eddy currents" in this metal, which in turn develop their own magnetic fields which induce eddy currents in the coil, resulting in the flux linkage between the two pieces of metal. The end result of the coil/metal interaction is a dampening of the magnetic field which surrounded the coil. This dampening is an effective detuning of the L-C circuit with additional inductance resulting in a new resonant frequency. As can be seen from Figure (5), a relatively small shift in frequency will result in large voltage variations. The operation of the circuit at the old frequency results in a relatively drastic reduction in voltage amplitude. This voltage reduction is the key indicator that determines the presence of metal within the sensor coil range.

2. Sensor Use

The practical operation of the sensors is relatively simple. In solo operation, the power source is set up with required voltage (14VDC) and the circuit is energized. Following a few minutes of elapsed time to allow for circuit warmup (initial high sensitivity falls off with time.) we ensure that the sense head is located in a metal free environment. At this time the potentiometer is adjusted until the controller LED indicates a positive condition (detection) and then backed off. Further test of the system is required to ensure that saturation is not possible. A target is moved into the sensor coil until a detect signal is acquired. The target is then removed. If the detect signal also drops off, the system is ready. If the sensor is saturated, and the signal remains after the target is removed, the potentiometer must be backed off and another trial completed. This condition is considered the maximum sensitivity setting.

In parallel operation, the interface distance which allows no complimentary saturation of either sensor must be established. This is done most easily by beginning setup of each sensor independently, as noted above, and then moving the sensors toward each other until saturation occurs and then increasing sensor-sensor distance just enough to end the interference.

C. STATIC SENSOR CHARACTERIZATION TEST PLAN

The first step in attempting to use these sensors as an ordnance identification/capture system lay in establishing the character of the sensor. The performance of the sensor against a variety of targets requires that the ability of the sensor to detect various types, geometries and aspects of targets be established. As such the following test plan was followed:

1. Preliminary tests

A series of preliminary tests were conducted on each sensor to determine basic sensor behaviors. The test plan determined the average range of detection for each sensor in three dimensions. The following information applies:

-All preliminary testing was accomplished with a standard target. The target is a cylindrical mild steel slug of 25.4 mm diameter and length of 38.1 mm.

-All preliminary tests were conducted using a power supply voltage of 14 volts DC.

-All preliminary tests were conducted using 20 repetitions to produce statistically acceptable data.

-All preliminary tests were accomplished in the solo mode with sensor coil and target long axes co-planar. See Figure (6) for more information.

Testing was accomplished using a wooden measurement device which held sensors in the required geometry and allowed a slow deliberate approach of target slug to the sensor. Approaches were made at a variety of positions ranging from the sensor tip to its base. Measurement of sensor to slug face distance was provided for in the device. Detection was considered accomplished when a steady LED was noted on the sensor controller board. Accuracy of the measuring device was estimated to be 0.5 mm.

2. Hysteresis Testing

Bench tests, using the above apparatus and conditions, were conducted to examine the hysteresis behavior of the sensors noted in preliminary testing. Measurements were taken to determine when detection occurred and the slug was then reversed in direction of movement and withdrawn from the sensor face until the detect signal was lost. The distance the signal remained on represented hysteresis of the sensor/controller.

3. Axial vs Perpendicular Approach to Sensor

A series of tests were conducted using the standard slug, and also an identical slug of twice its length, with two sensors operating in parallel at a distance of 115 mm. The tests were conducted to determine if target-sensor orientation affected detection range. The target was oriented with the long axis parallel and then perpendicular to the sensor's long axis and detection ranges measured. See Figure (7) for details.

4. Parallel vs. Solo Performance Tests

During testing to determine feasibility of sensor parallel operation variations in sensor performance were noted. It was found that dual sensor operation resulted in variation in range of detection. A series of tests were conducted to explore variations in range of detect for a variety of geometries for two sensor coils. The measurement device and other conditions noted in preliminary testing were used here. The only variation lay in the simultaneous operation of two sensor/controller systems. The purpose was to establish the optimal sensor performance geometry and quantify improvements. The photo in Figure (8) shows an example of the test orientations.

5. Target Material/Mass Tests

Tests were conducted under standard conditions with target slugs manufactured to the same dimensions as the standard slug, but of different types of metals. Metal types used were mild steel, type 401 stainless steel, aluminum, and brass. Detection ranges of the metal slugs were measured. Tests were also accomplished using slugs of standard mild steel but varying mass to determine effects of target size. All slugs were of 25.4 mm diameter but had lengths of 6.4, 12.7, 25.4, 38.1 and 76.2 mm. All tests were conducted in parallel, dual sensor operation geometry.

6. Ordnance Detection Tests

Five different types of inert U.S. submunitions, M42, M74, M32 grenades, Mk118 bomb and the 40MM projectile, were used in place of the standard slug to determine detection ranges. These munitions represent a wide variety of operating types, as well as materials used in submunitions. See Appendix B for data concerning specific submunition information (e.g. shape, material and operational background.) During this phase of testing, the submunitions were always oriented with their long axis parallel to that of the sensor, the position which provided most favorable detection ranges in earlier testing. Approach was made at mid sensor length. The sensors were placed in the dual operation geometry for these tests. All other conditions were as noted in preliminary tests.

D. TEST RESULTS

As noted in the opening of this chapter, preliminary testing on the self-contained, inductive proximity sensor indicated its unsuitability for this application. It had no detection capability except directly along its long axis at the sensor face. Its maximum detection range was approximately 13 mm. Therefore all reported results will pertain to the Model 85003 unshielded inductive sense head and EN401 controller.

1. Preliminary tests

The average detection range for the sensor was 20 mm. Best detection ranges were near the tip and base, with performance degrading rapidly near the threaded mounting portion of the sensor. Detection ranges were fairly constant along the entire length of the sensor, with no more than 2 mm variation at any point along its surface. There was symmetry in sensitivity about the longitudinal axis, resulting in a near-cylindrical volume of detection.

2. Hysteresis Tests

It was found that once the sensor established a positive detect signal the range to the target could be increased without loss of signal. In a series of twenty tests it was found that a positive signal was initiated at an average distance of 21.1 mm. The signal was maintained until the target had been separated from the sensor at an average distance of 43.4 mm. This feature, it was found, was established by the manufacturer to provide stability of response and provided better detection signals in later dynamic testing.

3. Axial vs Perpendicular Approach

Testing using the standard slug showed an average detection range of 45.9 mm when the target's long axis and that of the sensor were parallel (note the increased detection ranges evident when sensors are operated in a parallel configuration, this will be discussed at length in the next section.) A decrease in average detection range to 43 mm was noted when the two long axes were perpendicular. In tests with the longer target, the average parallel detect range was 53.3 mm while perpendicular detect range was only 47.4 mm. In both cases parallel orientation of long axis of target and sensor provided best detection range. Note that the centroid of the mass is at an increased distance in the perpendicular as opposed to the parallel configuration.

4. Parallel vs. Solo Sensor Operation

During the first tests to determine whether dual sensor operation would involve problems of interference requiring shielding or other resolution, it was found that by maintaining a distance of approximately 115 mm sensor face to sensor face, there would be no interference difficulties. Initial detection ranges which were obtained using the standard target and conditions were substantially improved. Tests completed to determine optimal sensor to sensor geometry and quantify these improved detection ranges showed that side by side parallel operation provided the best results. Typical detection ranges improved by 65 per cent over solo operation. The reasons for this improvement are not clear and were neither predicted not explained by the manufacturer. The issue will be addressed in Chapter VI.

5. Target material/mass tests

Tests to determine whether different metal targets of equal mass and geometry would provide varying detection ranges resulted in expected variations. Detection ranges were as follows:

	mild steel	stainless steel	brass	aluminum
average detection range (mm)	33.35	34.65	2.03	0
std deviation	.43	.33	.11	0
range relative to mild steel	1.0	.99	.06	0

Table 3.1

Manufacturer's literature provided correction factors of 1.1 for 400 series stainless steel, .5 for aluminum and .3 for brass, all relative to mild steel. Correlation of

this data to experimental results is reasonable for stainless steel but detection ranges for brass were much less than expected. The testing showed little or no ability to detect aluminum except near the sensor base where the aluminum target had a detection range of 10 mm.
Mass testing provided the following results:

target length (mm)	6.4	12.7	25.4	38.1	76.2
mean detect range (mm)	33.35	34.98	35.15	34.95	36.95
std dev	.43	.11	.24	.15	.15

Table 3.2

Increased mass showed a general trend of increased detection range, however, the relationship is far from linear and points toward fairly stable detection ranges, beyond a detectable minimum mass.

6. Ordnance Detection Ranges

The following table provides average detection ranges for the submunitions tested; the standard slug was included as a control/comparison:

	target slug	M32	M74	M42	40mm	Mk118
ave range	39.6	20.0	38.9	44.5	5.0	21.2

Table 3.3

Test results reflect best detection ranges for dense, ferrous submunitions, reasonable ranges for larger aluminum bodies and poorest detection for small aluminum ordnance. All of the submunitions, however, could be detected using these type of sensors.

IV SWEEP DEVICE DESIGN

A. TEST VEHICLE DESCRIPTION

The test bed chosen for this research was a radio controlled, electrically powered hobby car manufactured by Radio Shack. This vehicle represented one of the most robust, sophisticated electric hobby vehicles available in the market today. It was equipped with proportional speed and steering control, trailing arm front suspension, and differential gears for the rear drive wheels. Four wheel spring suspension was provided. A removable body shell allowed mounting of controller and instruments on a wide, flat chassis. The photo in Figure (9) shows details of the vehicle. The following specifications apply:

Manufacturer:	Radio Shack
Model:	Rock Runner
Part number:	60-143
Power Supply:	Rechargeable DC Ni-Cad batteries 7.2 Volts
Transmitter frequency:	27.255 Mhz
Dimensions:	length-17 in width- 11.25 in height- 8.25 in
Weight	6 lbs
Ground clearance:	1.62 in
Tire diameter	5.5 in

Turning radius: 32.25 in

Optimal payload: 3.5 lbs

Field tests of the stripped-down vehicle showed that it was quite robust, capable of operating in heavy grass and uneven terrain. Payload capability ranged from 3.5 to 6.0 pounds, depending on the terrain. In use, the vehicle was capable of operating for periods of approximately one half hour before the drive battery was exhausted.

B. EVOLUTION OF THE DESIGN

Every designer has a preconceived notion concerning the form of the solution to his design problem. The end result of this design process was a radical change from the ideas which I held at its beginning.

At the outset of the project, the design envisioned was one of a sweep arm which contained one or more magnetic sensors along its length, anchored with a universal joint at the center of the vehicle front end. The sweep arm was to be of cantilever design, with a gate hinge support design, and possibly be capable of actually rotating in an arc, driven by a dc motor. In short, the design was a small vehicle which proceeded forward while sweeping sensors in an arc ahead of its path. This is almost a direct parallel to the method currently used by EOD technicians operating hand-held magnetometers in the field.

The development of a prototype arm, and completion of initial sensor testing, uncovered immediate problems with the planned design. Short sensor ranges would require quite a large number of sensor coils deployed along the arm to effect a swath of the required size. In addition, these sensors would need to be driven with power supplies and supported structurally. The cost, power and weight considerations were such that it was clear that another approach was required.

Due to the small detect distance and sensitivity to orientation of the sensors, the advantages of a system which would minimize submunition-sensor distance and provide optimal orientation were obvious. The solution found used a plow design. The development of a plow concept with sensors aligned along trailing edges would allow the vehicle to use its driving power to force submunitions into a "slipstream" along the edge of the plow where they would be optimally oriented to the sensor for detection. In addition, placement of the sensor near the end of the sweep edge would allow for the possible capture of the munition while it was in contact with the sweep plow. Measurements of the vehicle speed, sensor and microprocessor response times and capture arm deployment time lead to the development of the design pictured in Figure (10).

Additional considerations which were addressed during design included sweep weight, non-metallic sweep construction requirements, optimal geometry of sensors for improved complimentary detection performance, submunition size/height of sweep above deck, and maneuvering constraints. Initial tests using a u-joint support, proposed in the initial design, showed difficulty in supporting sensor weight, steering, and providing rigidity for submunition plowing. A rigid mount was designed which would use a freely rotating caster to support the sweep front while the rear was rigidly fastened to the vehicle. Later testing in the field showed that additional modifications in extending the depth of the plow edge and adding a rigid support to reduce sweep bouncing improved sweep results. Figure (11) is a photo of the sweep operating on the test vehicle.

V. SWEEP DEVICE PERFORMANCE

A. TEST PLAN

1. Controlled Probability of Detection Tests

The first step in evaluating sweep device performance was to determine the probability of detection of the sensors when a submunition was passed by the sensor in a controlled fashion. In order to ascertain this probability of detection a method of correlating sensor detection to submunition exposure was required. It was determined that LED visual signals would not provide adequate accuracy of signal detection. Instead a measurement of LED voltage output would provide positive, accurate indication of submunition detection, as well as additional information on sensor behavior and a more suitable form for microprocessor interface. Measurements of the LED signal voltage, provided by the controller following sensor signal processing, allowed for the positive determination of target presence. A single channel of data was collected with a two conductor wire connected to the LED outputs providing voltage signal produced by the controller for each test run. By monitoring this voltage and using an A/D converter with a personal computer and software capable of sampling the voltage at time intervals, a log of the sensor behavior was obtained. Sampling quantities were set to allow complete event monitoring while using a frequency of 100 hz during target sweep or presentation of targets. In this fashion a complete time history of sensor output was derived. By comparing the sensor output to the known sequence of events, sensor performance could be quantified.

For these tests, and all that followed, the sensors were mounted on the sweep and test vehicle in the configuration shown in Figure (12). Note that the geometry was such that complementary dual sensor operation was not possible. This was a result of imposed minimum sweep widths. Tests were conducted with an effective voltage of 14.4 volts provided to the sensors via two 7.2 volt rechargeable nicad batteries wired in series and mounted on the rear of the vehicle. Voltage variations required significant adjustment of the sensor potentiometers to attain reasonable detection sensitivities. The sensor controllers were harnessed to the top of the vehicle, with LED available to provide visual detection signal.

The sweep and vehicle test bed were oriented at a slight angle to the horizontal and submunitions were slid into a favorable detection area using a metal ramp. Measurements of sensor output provided detailed proof of sensor detect/non-detect. Using a series of <u>100 submunition exposures</u> for each type a statistical percent detect was obtained.

2. Dynamic Laboratory Tests

Following the completion of all controlled detection tests, the sensor systems remained mounted on the remotely operated vehicle for a series of dynamic tests requiring active movement and sweeping to be conducted in the laboratory. The signal was collected in the same manner as described in the previous section. All tests were conducted on a smooth, level laboratory floor.

a. Detection Signature

Four test runs were conducted on each of five ordnance types to determine whether the sensors would detect the ordnance in this configuration. During each test an ordnance piece was placed in a favorable detect orientation at the front of the sweep, see Figure (13) for details, and the vehicle driven forward to force the ordnance along the sweep and into sensor range. The tests were accomplished using 500 sampling points at a frequency of 100 hz, or one sample point each .01 seconds.

b. Multiple Ordnance Detect

A series of tests were conducted to determine whether the sweep was capable of detecting one or more different pieces of ordnance during sweep operation. Four pieces of ordnance were arranged in a line ahead of the sweep at intervals of 2 feet. The vehicle was then driven forward and data collected. Once again tests were accomplished using 500 sampling points at a frequency of 100 hz.

c. Laboratory Probability of Detection

Once the capability of the sensor and sweep to detect multiple submunitions was established, a series of tests were accomplished using five submunitions of each type aligned in front of the sweep and vehicle at intervals of one foot. The vehicle was then driven straight through the five munitions and a record of the sensor detects obtained. In this manner the dynamic percent detect for the system in the laboratory was obtained. All tests were accomplished on a smooth laboratory floor.

d. Field Probability of Detection

Using the same equipment and procedures noted above, tests were conducted under more difficult conditions on a grass and dirt surface. Due to limitations in navigation and driving, a small course was constructed to ensure contact of the sweep and submunition during test vehicle operation. Details are in Figure (14). Once again sensor performance was monitored and percent detection derived from the data. Due to problems involving difficulty of the sweep engaging submunitions in the grass noted during the first series of tests, a slight modification to the sweep was made and the series of tests repeated. Details of the problems and modifications will be discussed in the next section.

B. RESULTS

1. Controlled Probability of Detection Testing

Tests conducted to ascertain the probability of detect for most favorable passage of the submunition past the sweep/sensor arrangement showed the results found in Figure (15). Two of the five submunitions had perfect detection rates while the remaining three had rates of 97, 87 and 87 per cent. The variation from perfect can be attributed to irregularities in the submunition surface occasionally causing some of the test specimens to bounce away from the sensor as they approached.

2. Dynamic Laboratory Testing

Tests conducted to determine the feasibility of using the sweep/sensor configuration for submunition identification confirmed this capability. Figures (16) through (20) provide examples of typical voltage readouts for individual detection events on each type of submunition. Similarly Figures (21) through (25) display printouts of signatures for multiple (five) submunition encounters.

a. Laboratory Probability of Detection

Repetitive tests to determine probability of detect during a dynamic sweep in a controlled environment provided results summarized in Figure (26). Each of the submunitions experienced a drop of approximately 10 percent in probability of detect. This can be attributed to vagaries of approach geometry and the increased possibility that the munition would not encounter the sensor in an optimal orientation.

b. Field Probability of Detection

Tests conducted on a rough grassy surface (details of the surface contour and composition are available in Appendix C.) provided results shown in the graph of Figure (27). Obvious difficulties in maintaining the sweep leading edge in contact with submunitions during sweeping were noted. The sweep edge frequently rolled over smaller munitions, although frequently still detecting them. In other cases, the vehicle bounced along the rough surface, riding up and over submunitions. It was decided that modifications to the sweep would improve its ability to physically sweep submunitions, and that this would in turn increase detection rates. Data from the modified sweep are provided in the graph in Figure (28). Additionally percentage of submunitions physicallly swept are provided in the Figure (29) to allow correlation between the two.

VI. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

The first step in establishing the feasibility of using small robotic vehicles to conduct submunition clearance has been successfully completed. It was found that rugged, self-contained, magnetic induction sensors mounted on a small, remotely-operated vehicle, which operated in an obstacle-free environment, provided probabilities of detection ranging from 78 to 94 per cent, dependent upon the type of submunition tested.

Using a sensor system integrated into a plow sweep design provided a high percentage sweep and detect rate for metallic submunitions which are located in a relatively obstacle free environment such as ranges or runways. The plow provided for increased detection rates with faster area coverage than would be possible with non-contact sweep designs.

The detection ranges and sensitivity of the magnetic induction sensor system can be improved by operating at least two sensors in optimal parallel geometries which provides for symbiotic performance improvement. While the mechanisms underlying this behavior are not well understood, its existence was clearly documented in this research.

The detection signals provided by the sensor/controller system provide unambiguous voltage signatures which should be easily adaptable to evaluation by a microprocessor unit. A variety of subsequent desired actions such as marking or pickup can then be initiated. Using signature data it may be possible to actually identify the specific submunition or reduce non-ordnance false targets detection rates.

The probability of submunition detonation and subsequent damage of the sensor/vehicle when operating in the plow sweep mode used in this research is unknown. This probability will definitely vary depending upon the type of submunition swept and conditions of operation. Live range testing will be required to ascertain specific detonation rates and improvements to the system which may reduce these rates.

Results of preliminary and dynamic tests conducted with the unmodified sweep showed that detection of submunitions occurred even when the target was not forced into contact with the sensor face. This detection ability may allow for the use of lightweight vehicles and sensor arrangements in searching for, or identifying, minefields or other buried munitions.

Behavior of the sweep in heavy grass indicates that weight of submunitions is a consideration in operation of the system. The pushing ability of the drive vehicle is a limiting factor. In these tests, the electrically driven vehicle began to encounter difficulties with heavier submunitions weighing 1.3 lbs.

The speed of the drive vehicle and sweep also appeared to affect the performance of the system. Speeds of approximately 1 meter per second provided what appeared to be optimal ability to move larger submunitions using the plow, while not causing exceptionally short voltage signatures or unstable behavior of the vehicle. Laboratory speed measurements showed vehicle speed on smooth surfaces ranging up to 2.8 meters per second. While no effective method of providing constant speed control was devised for this research, microprocessor speed control using speed sensor feedback appeared easily attainable in the next phase of development.

B. RECOMMENDATIONS

A number of additional areas of research can be pursued as a result of information derived from this thesis. The following recommendations for further study are provided:

1. Speed control and navigation of test vehicle/sweep

The ability to equip the current test vehicle and sweep with speed sensors, steering orientation, positional sense, and a self-contained, programmable microprocessor capable of using this data to drive specified missions, will allow for development of programmed search patterns and provide additional data concerning sweep effectiveness. It is the next logical step in developing an autonomous vehicle as well. Incorporation of DGPS or other local navigation system into the system may also prove valuable, although not necessary if random searching is allowed.

2. Susceptibility to submunition detonation

Tests should be conducted to ascertain the probability of particular submunitions to detonation when subjected to movement by the sweep plow during operation in the projected environment. Damage to the vehicle and sweep during this detonation must be established. Additional work to alter sweep plow design to reduce detonation rates or reduce damage to the systems should also be addressed.

3. Sensor vehicle evaluation

Evaluation of other commercially available vehicles which might provide more robust platforms with greater pushing abilities, and duration of operation, should be considered. Electrical and internal combustion power sources should be explored.

4. Development of sensor suite

The use of additional sensors, in concert with the magnetic induction type used here, should provide greater detection rates, fewer false alarms, and in general, greater flexibility in using microprocessor abilities to accurately discern desired targets.

APPENDIX A. FIGURES

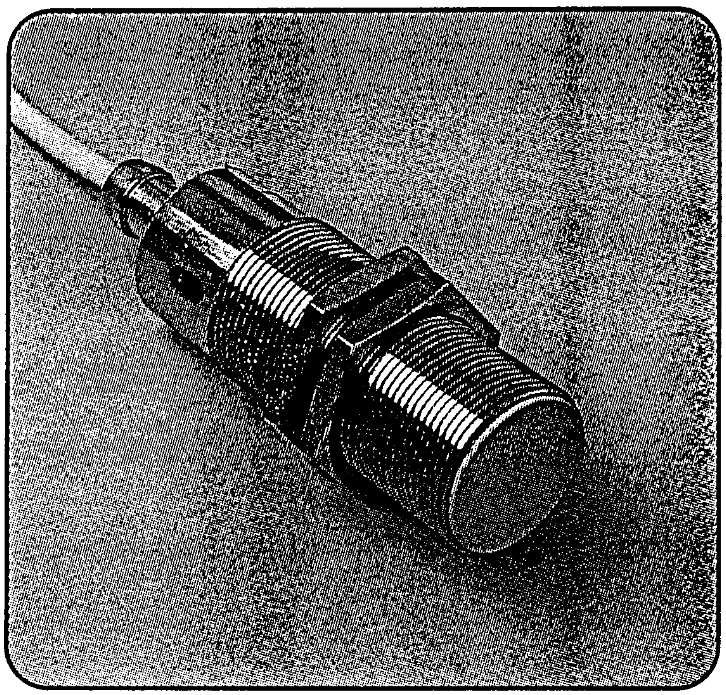


Figure 1. Model ET1AN2B Self-contained, Unshielded Proximity Sensor

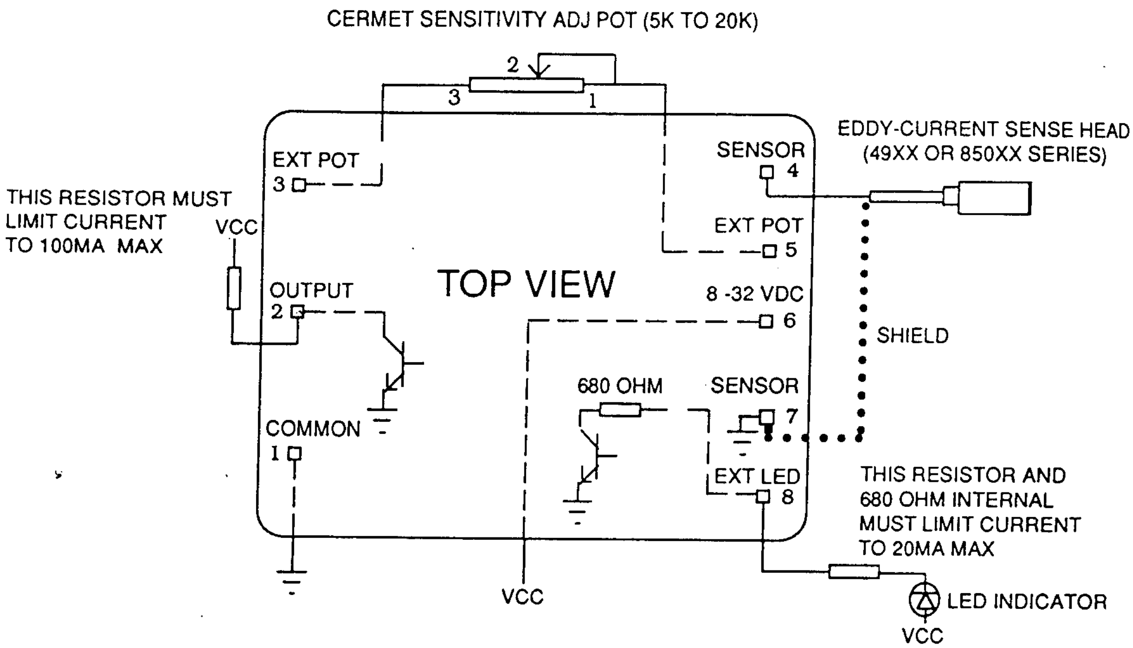


Figure 2. EN401Controller and Model 85003 Unshielded Inductive Sense Head Wiring Schematic

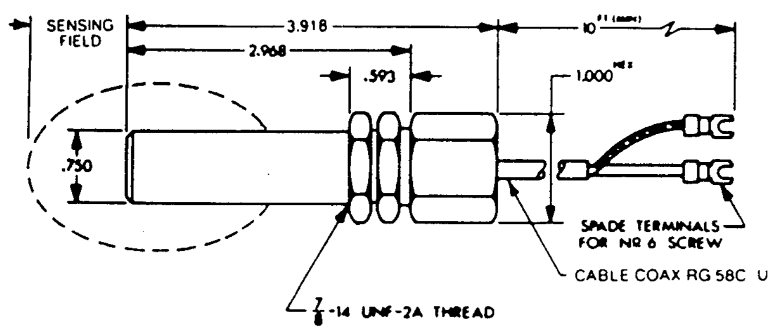


Figure 3. Model 85003 Sensor Head Construction

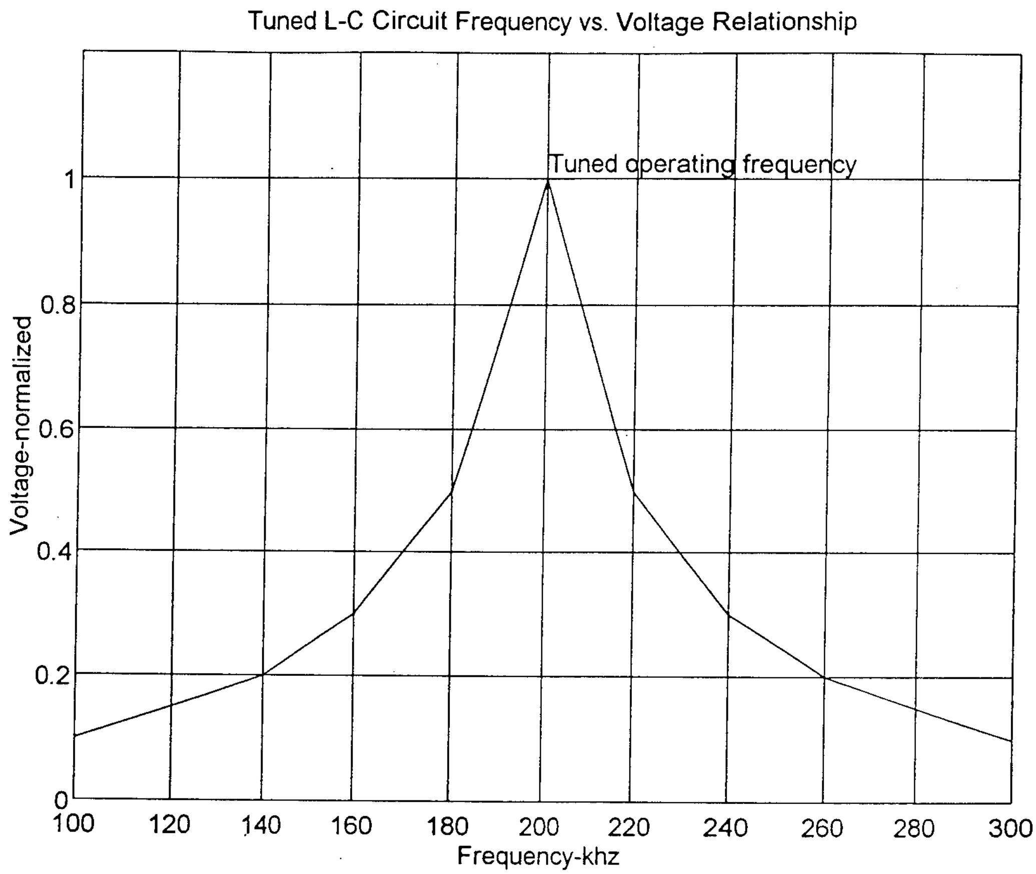


Figure 4. Tuned L-C Circuit Frequency vs. Voltage Relationships

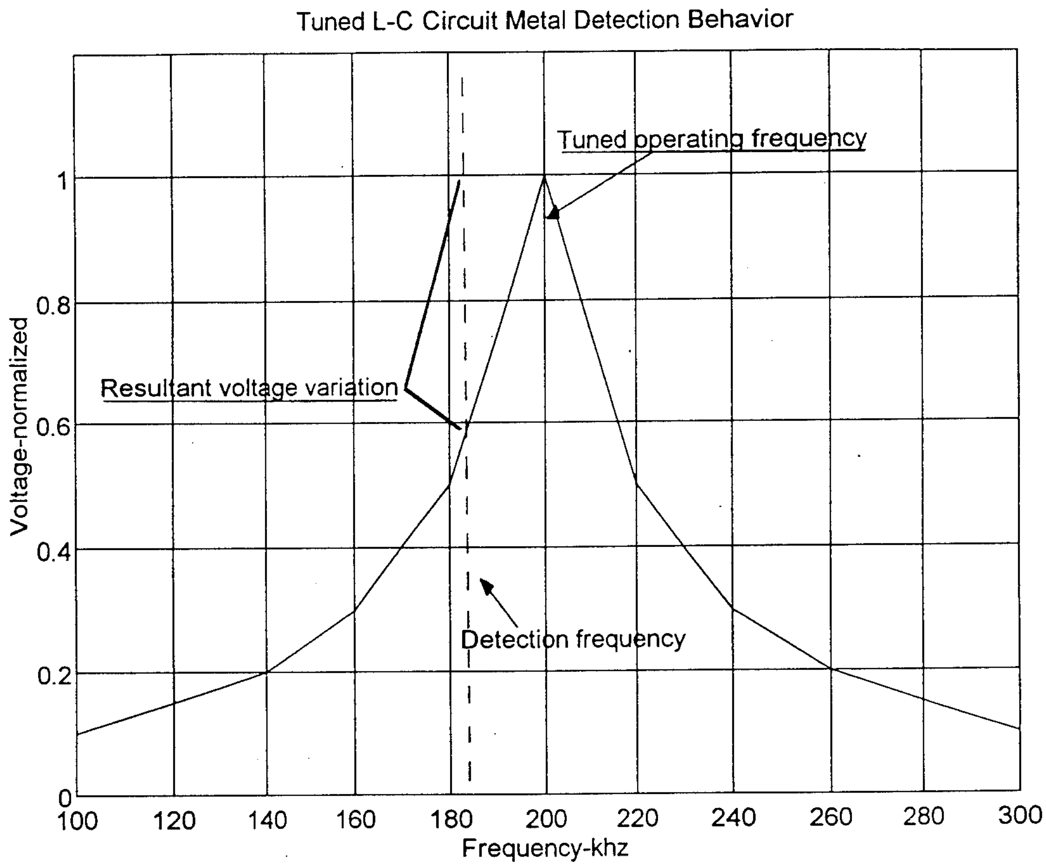


Figure 5. Tuned L-C Circuit Metal Detection Behavior

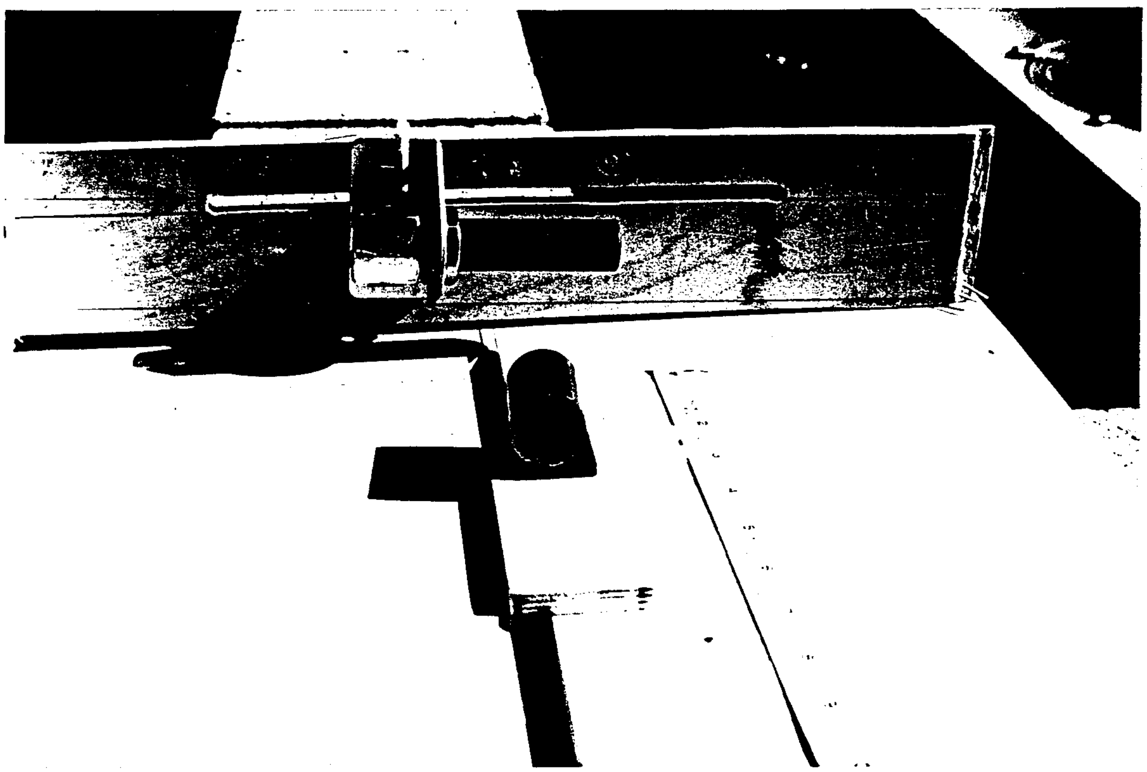


Figure 6. Sense Head/Target Orientation-Preliminary Testing

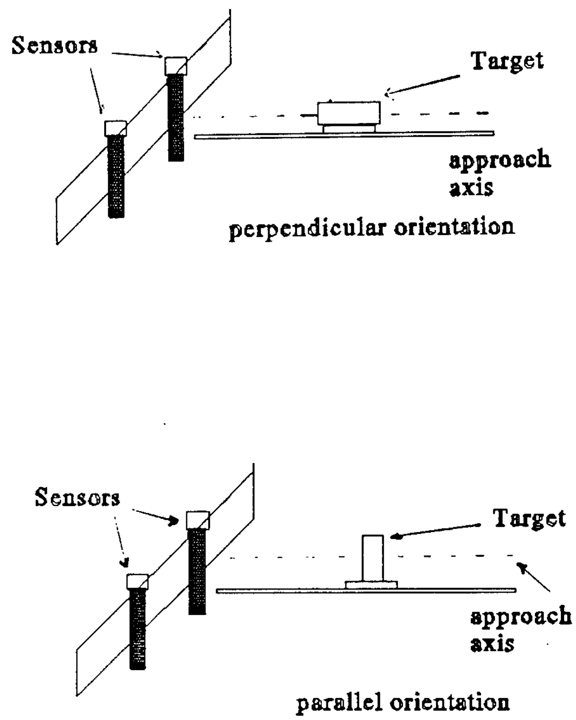


Figure 7. Parallel/Perpendicular Sense Head/Target Test Geometry

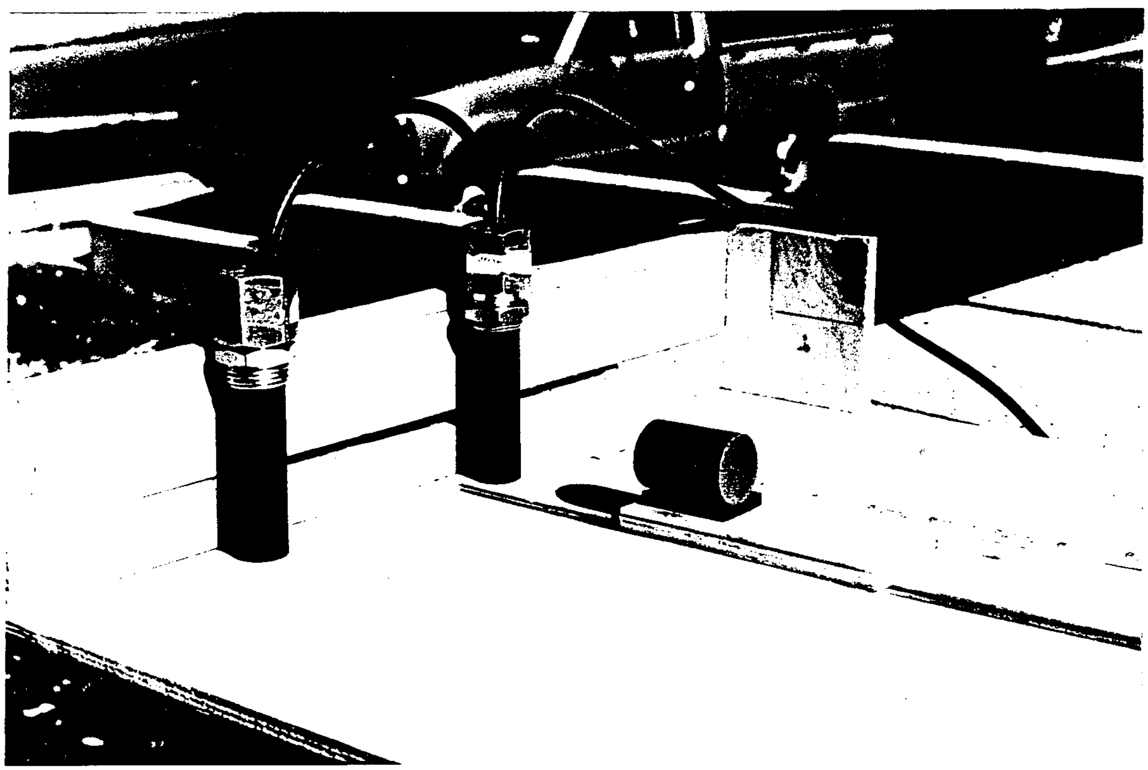


Figure 8. Parallel Sensor Operation Test Geometry

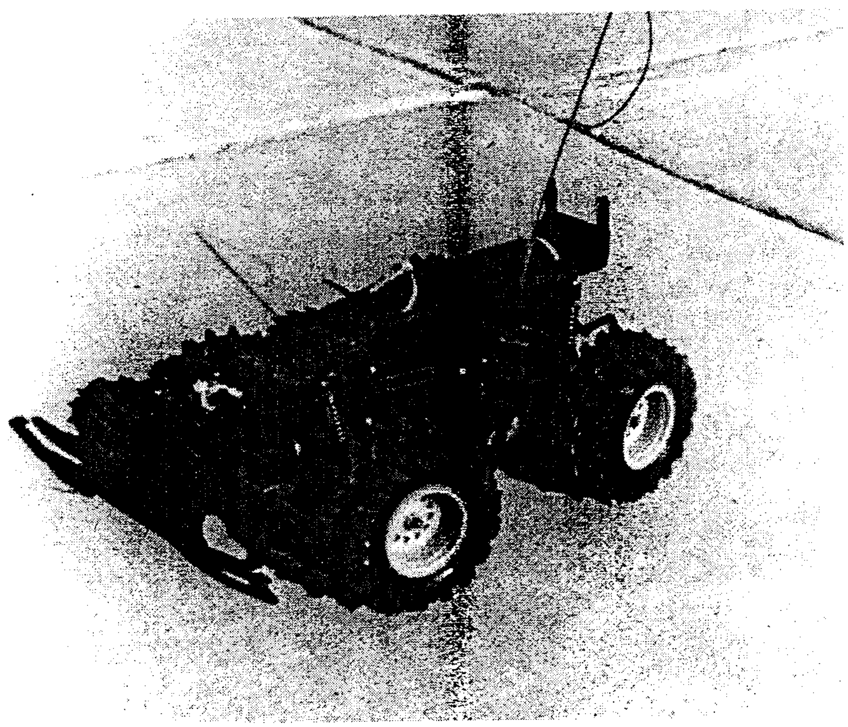


Figure 9. Radio Controlled "Rock Runner" Test Vehicle

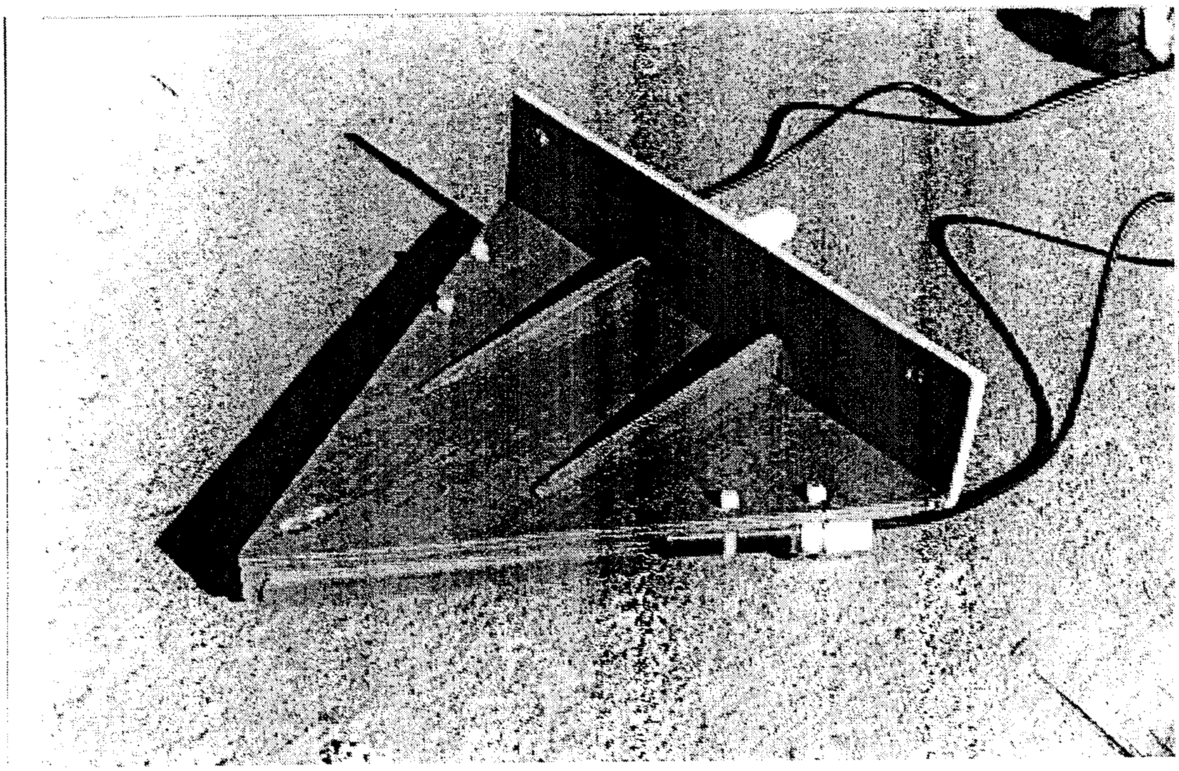


Figure 10. Sweep Design

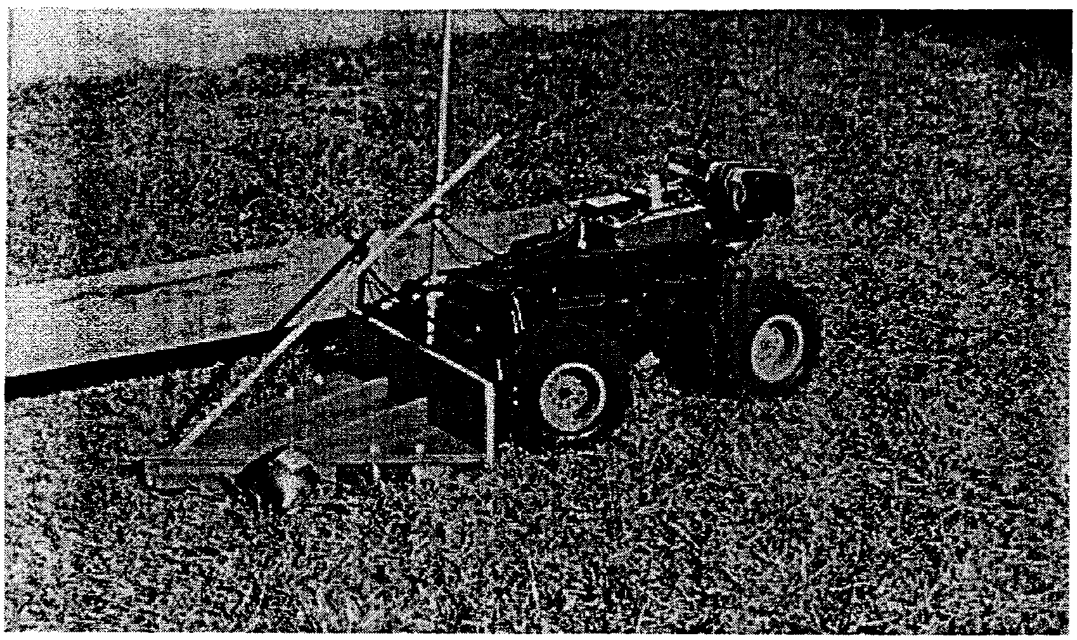


Figure 11. Sweep Configured on Test Vehicle

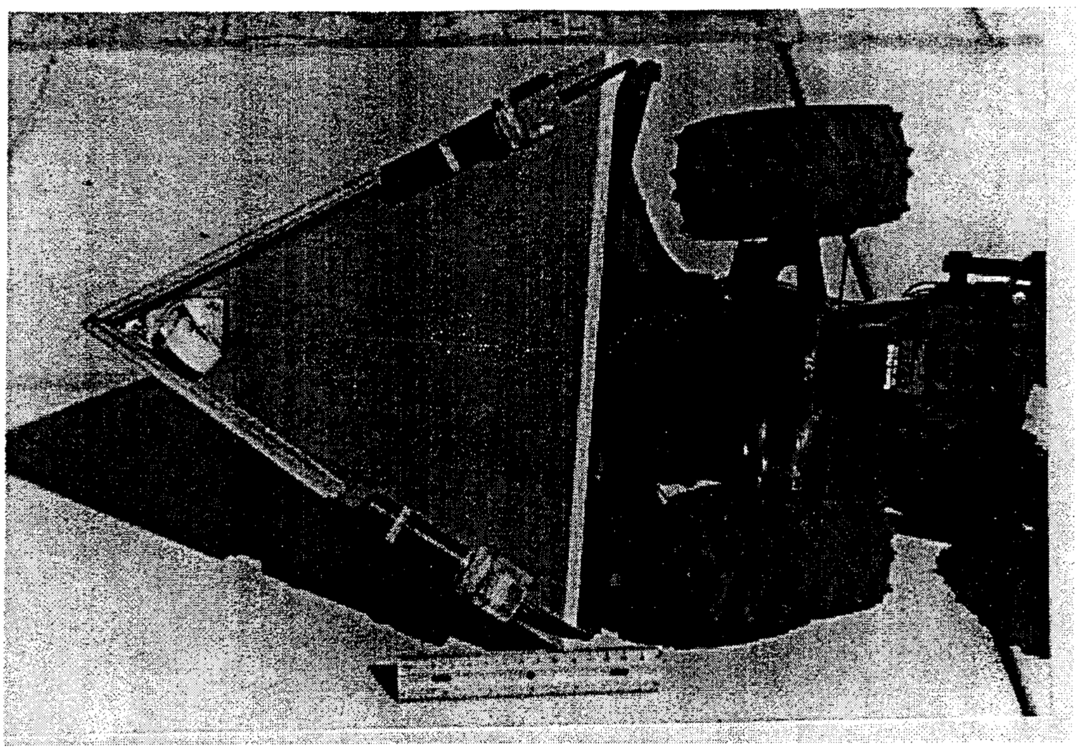
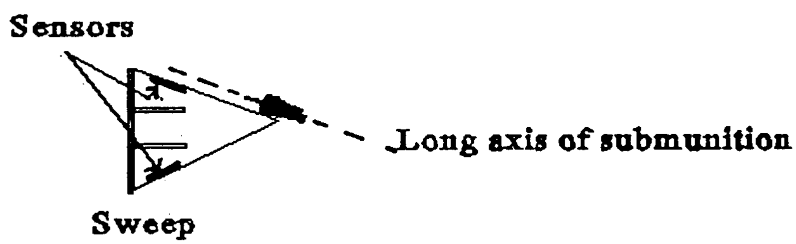


Figure 12. Sensor Test Mounting

Figure depicts position of submunition prior to test commencement



For spherical submunitions no specific orientation was chosen

Figure 13. Laboratory Detection Signature Test

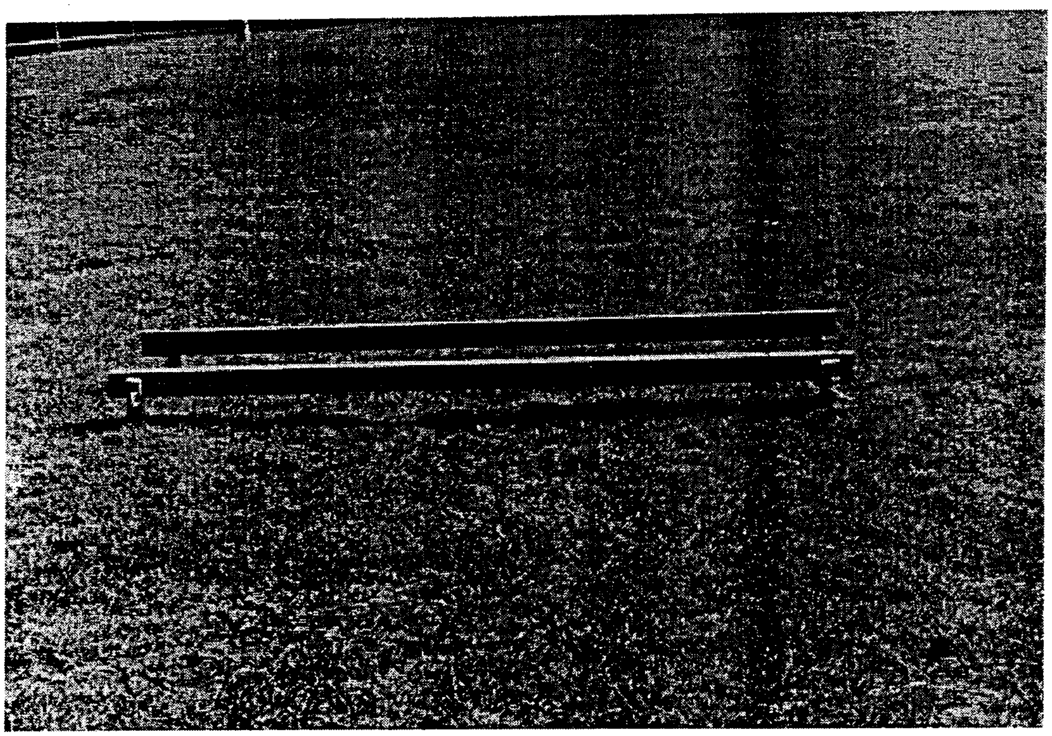


Figure 14. Field Test Setup

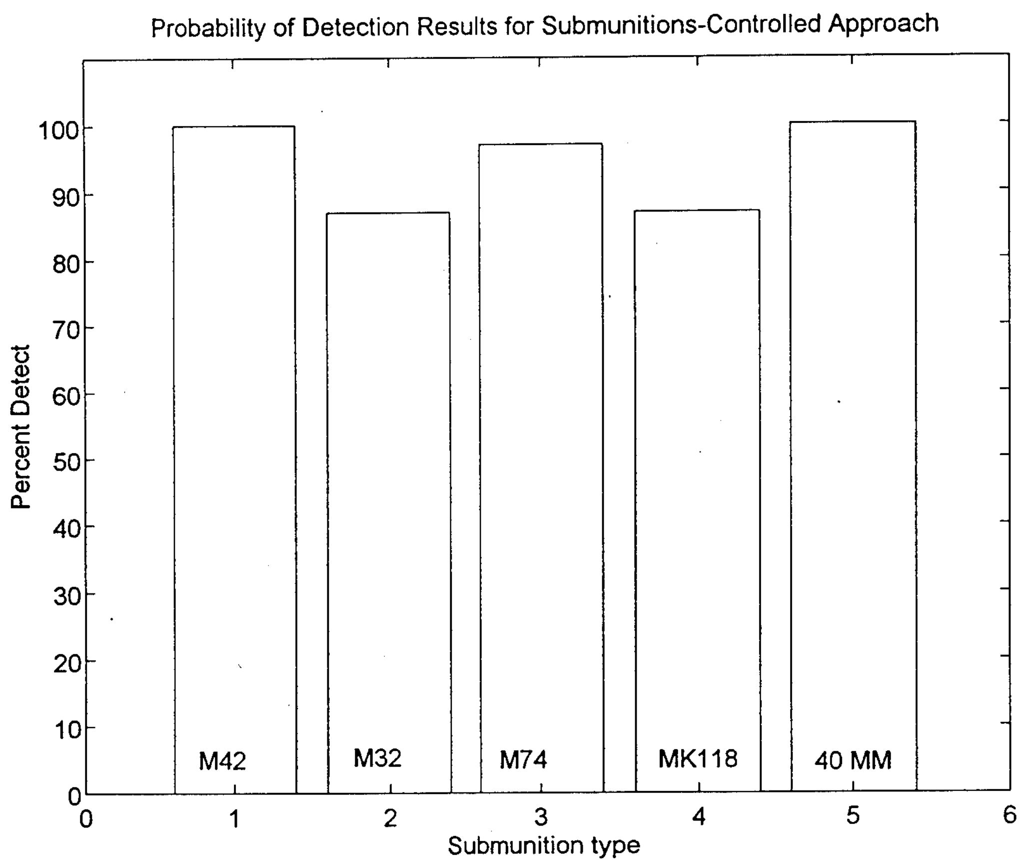


Figure 15. Controlled Probability of Detection Results

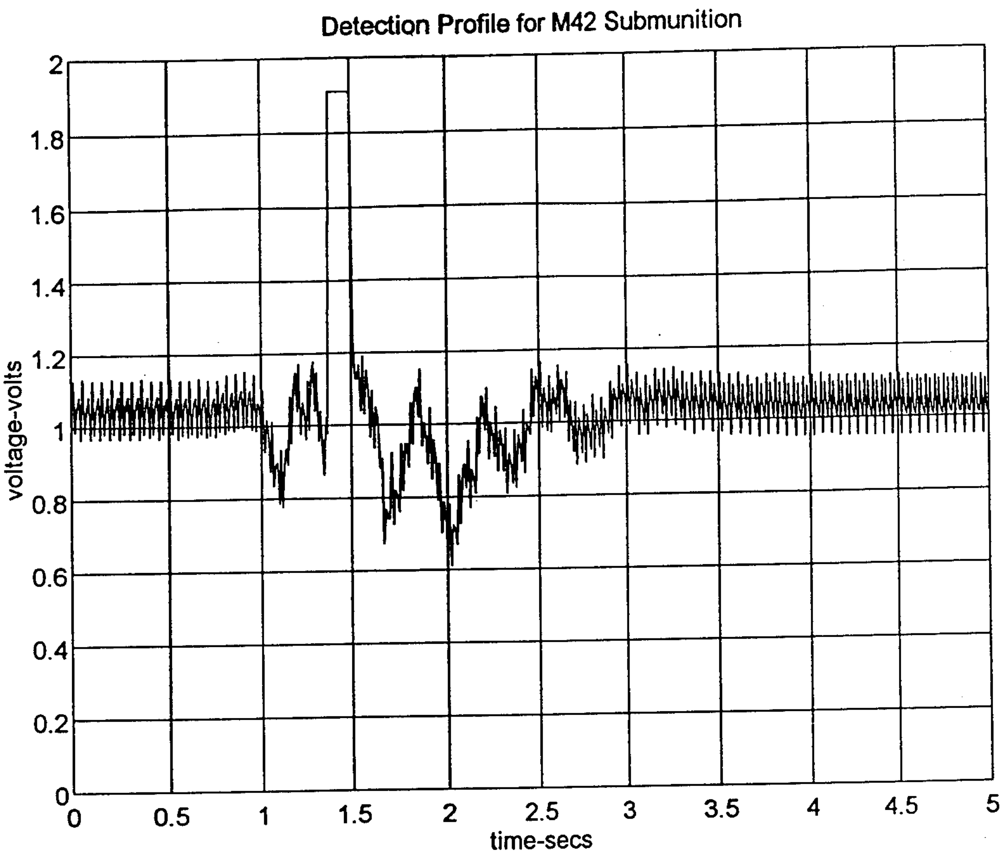


Figure 16. M42 Detection Signature

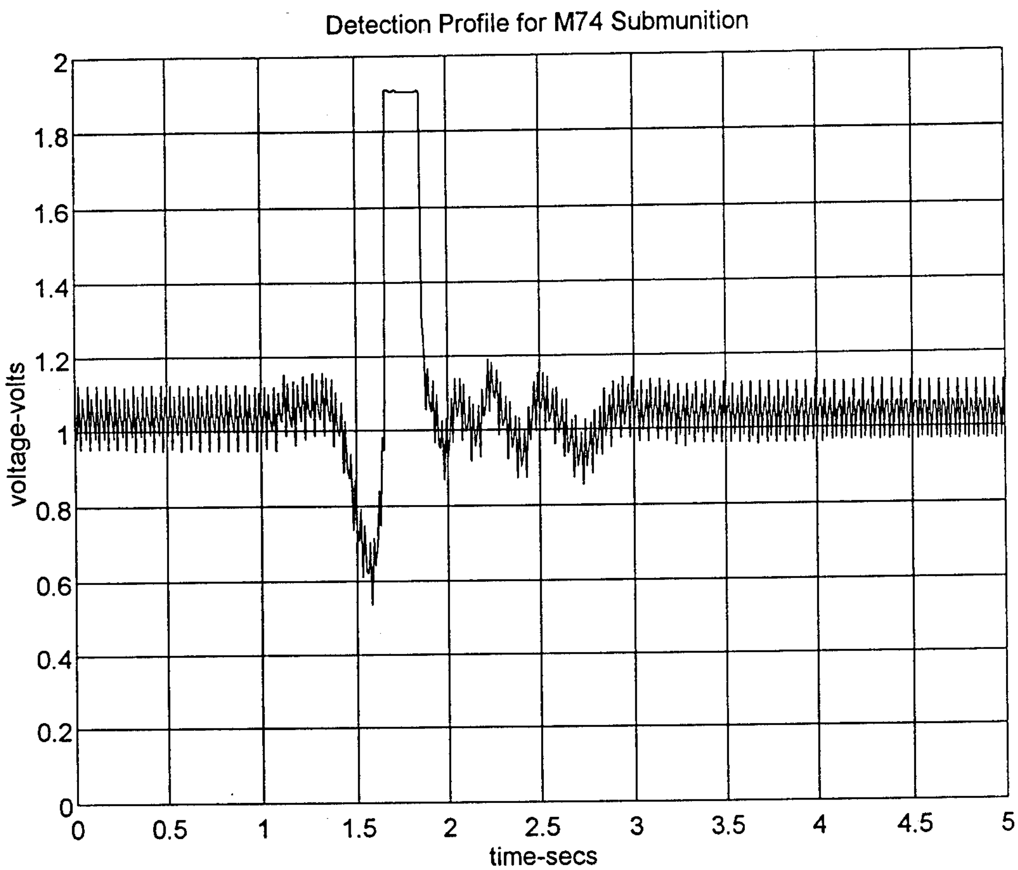


Figure 17. M74 Detection Signature

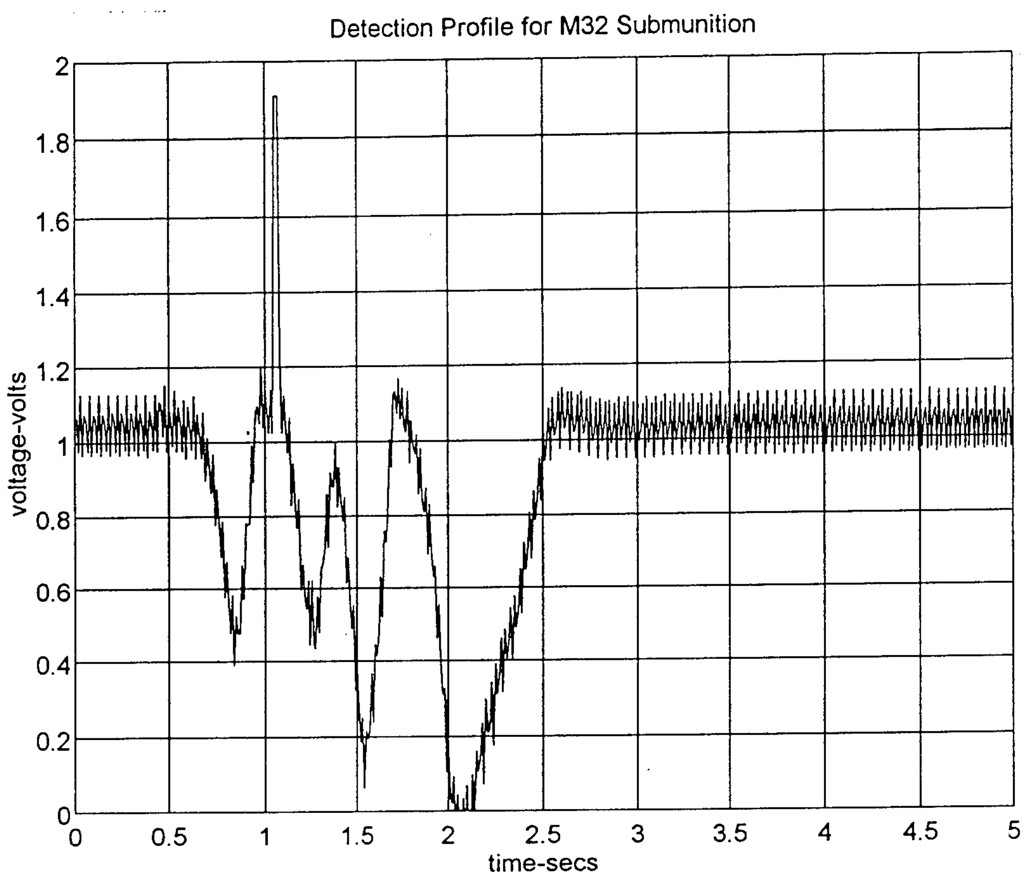


Figure 18. M32 Detection Signature

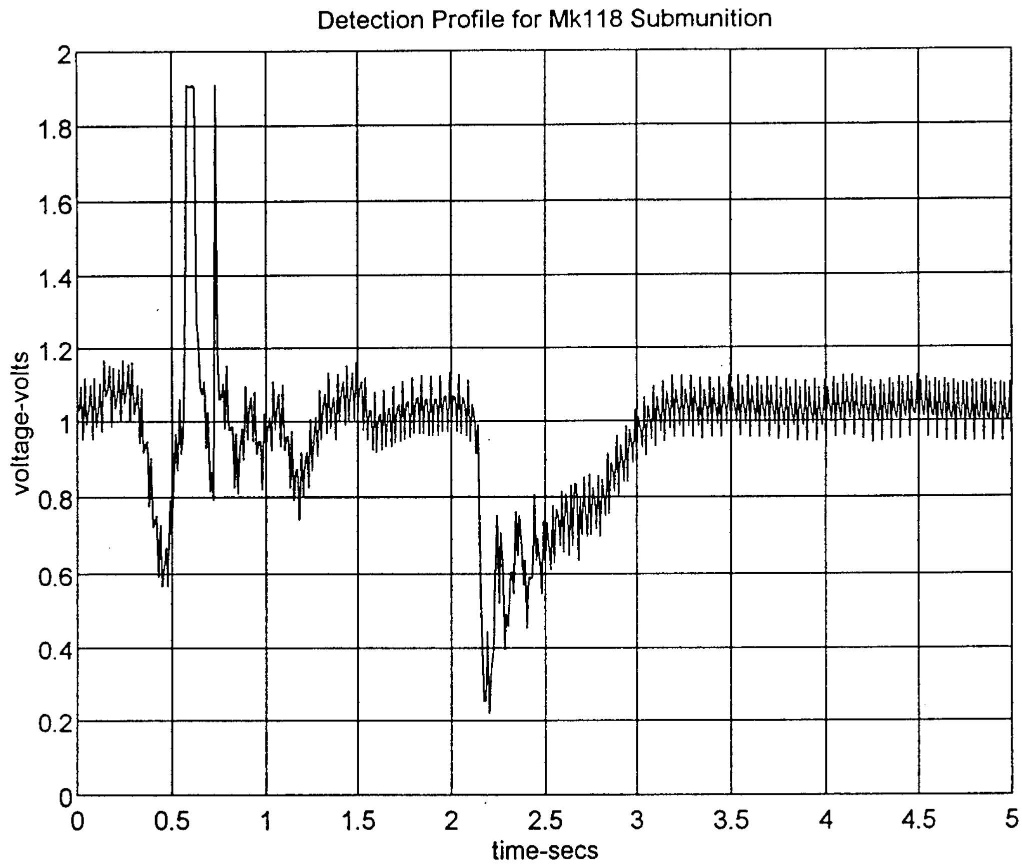


Figure 19. M118 Detection Signature

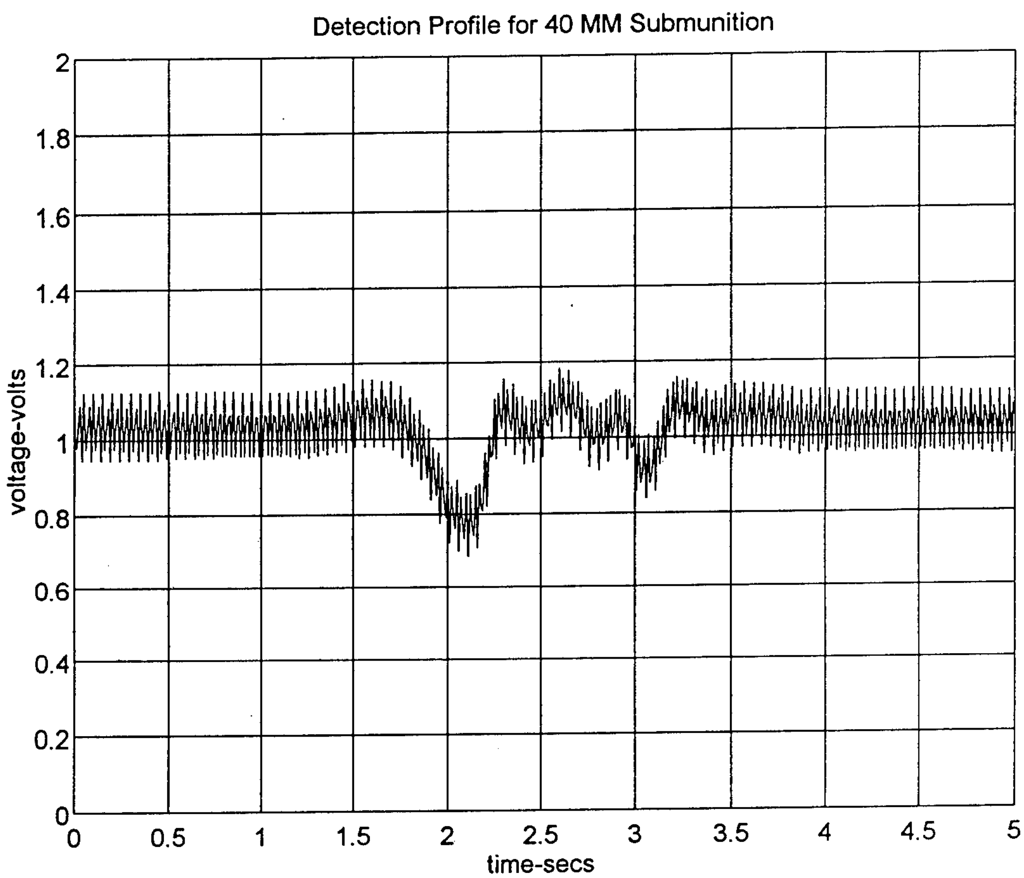


Figure 20. 40 MM Detection Signature

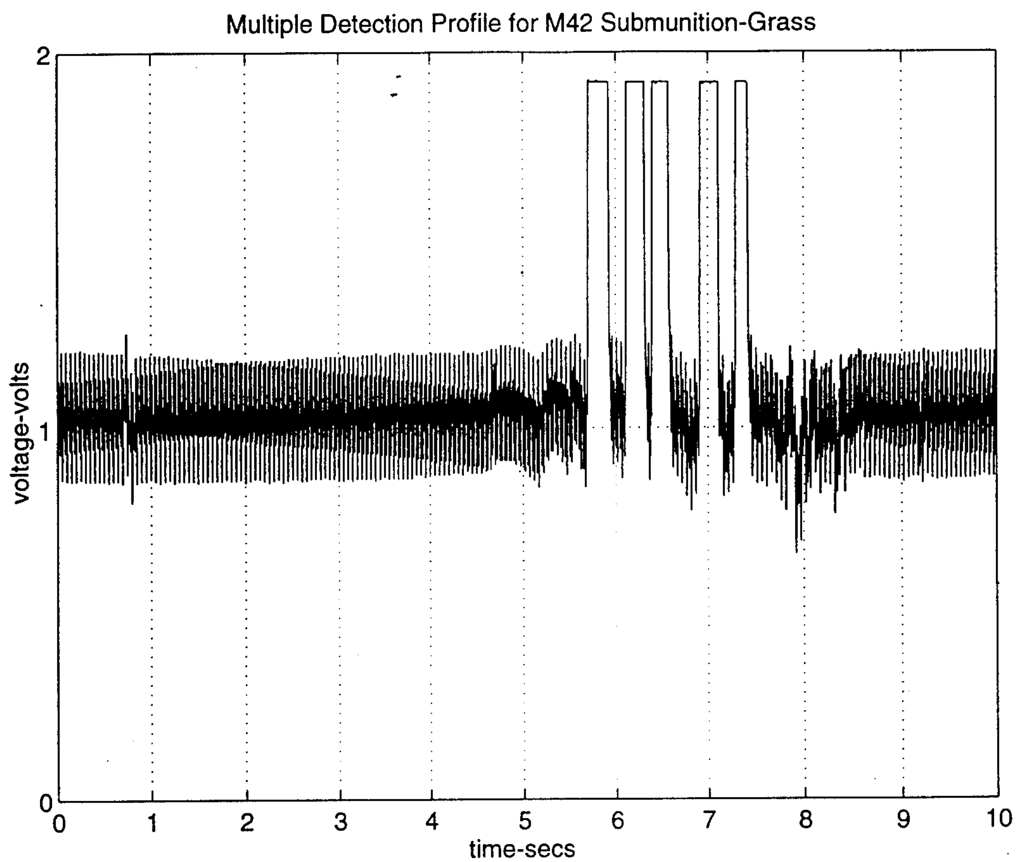


Figure 21. M42 Multiple Encounter Signature

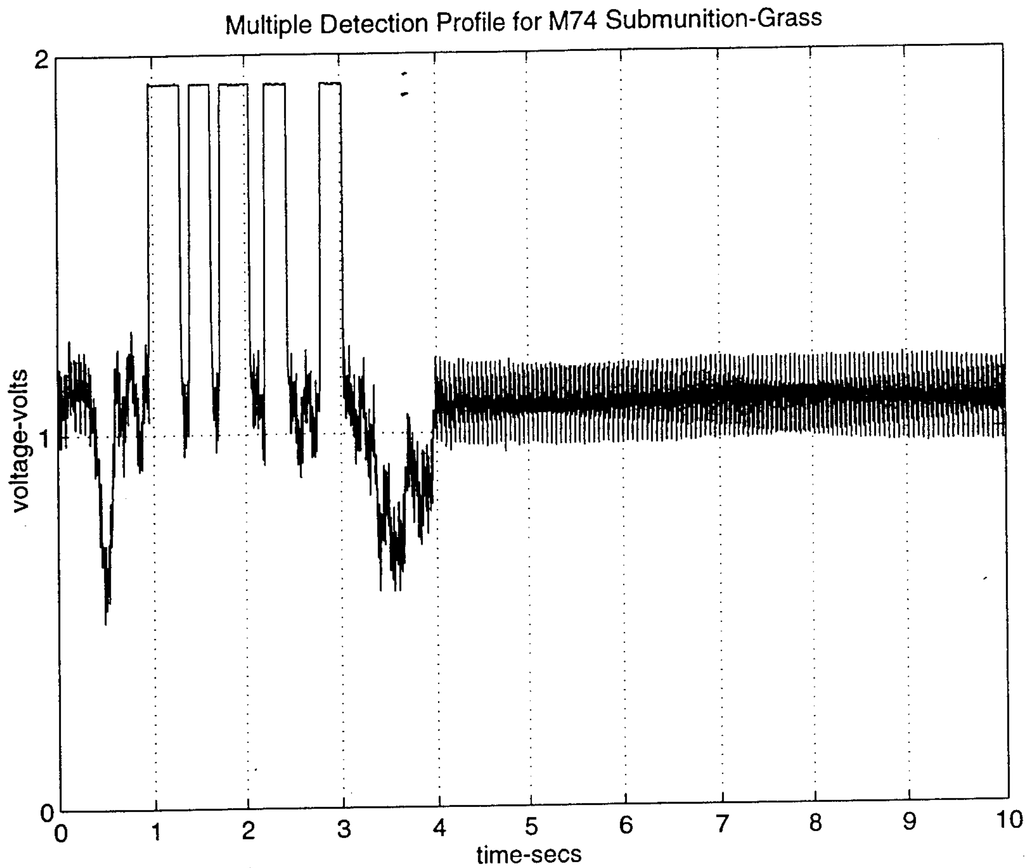


Figure 22. M74 Multiple Encounter Signature

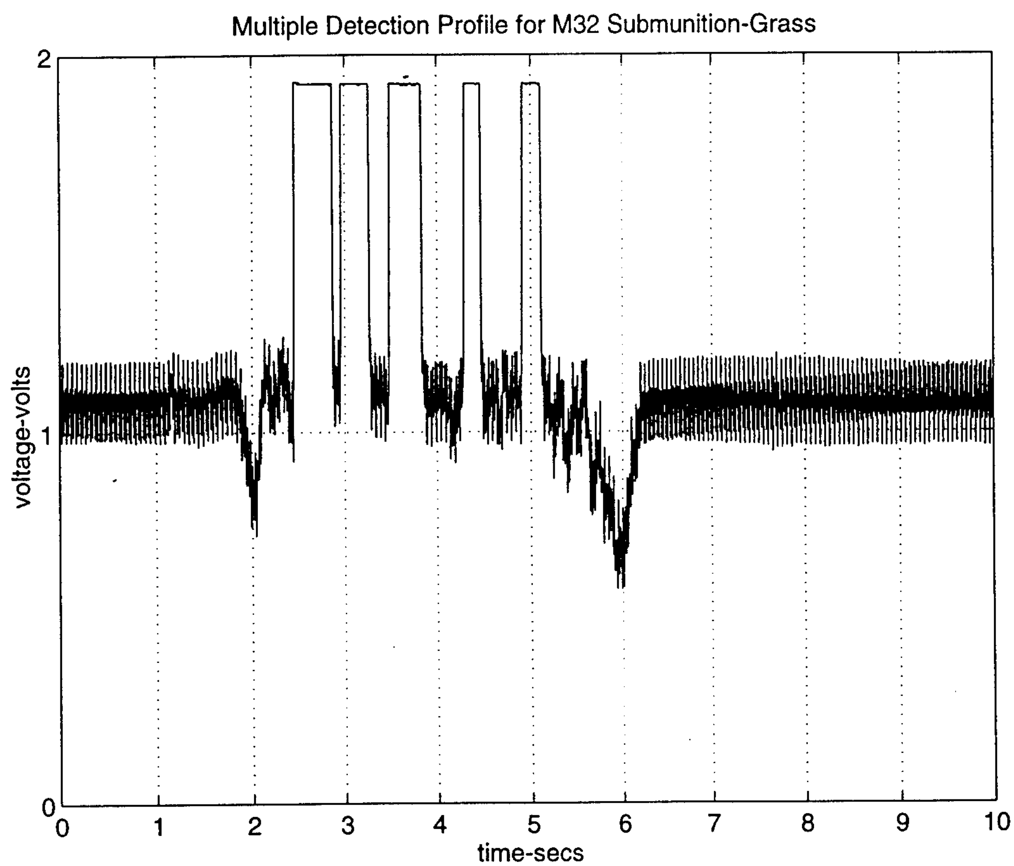


Figure 23. M32 Multiple Encounter Signature

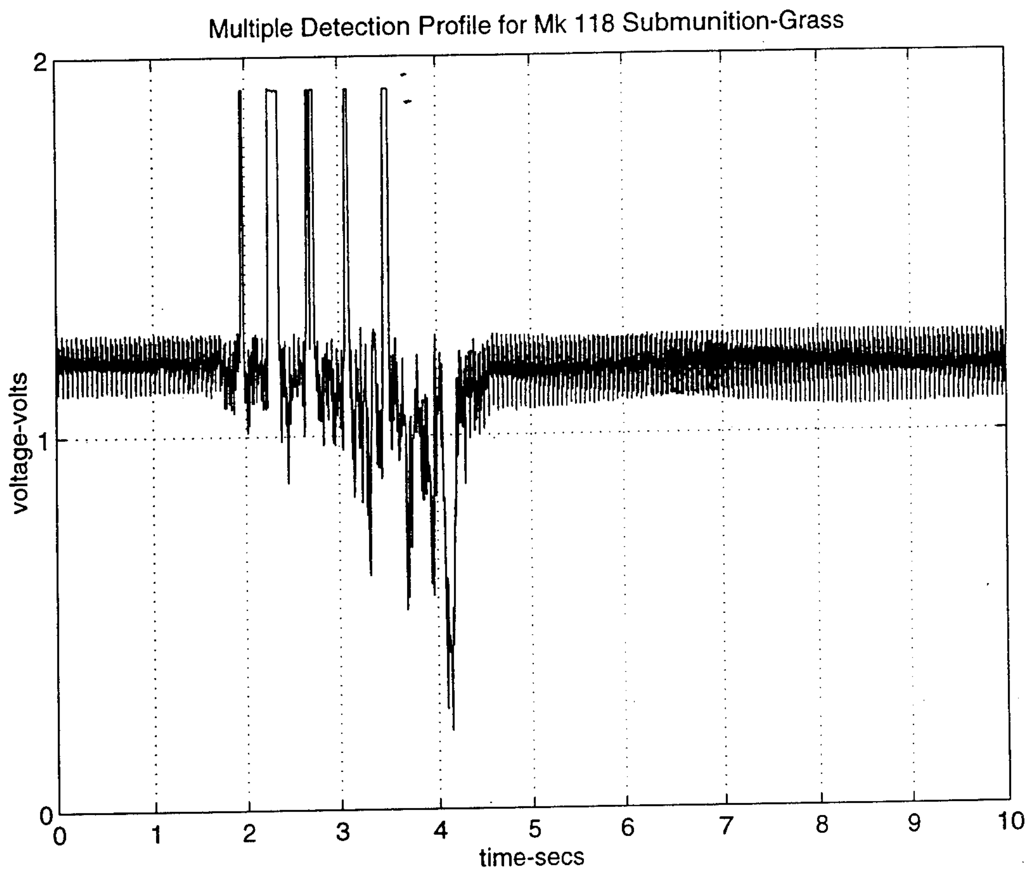


Figure 24. M118 Multiple Encounter Signature

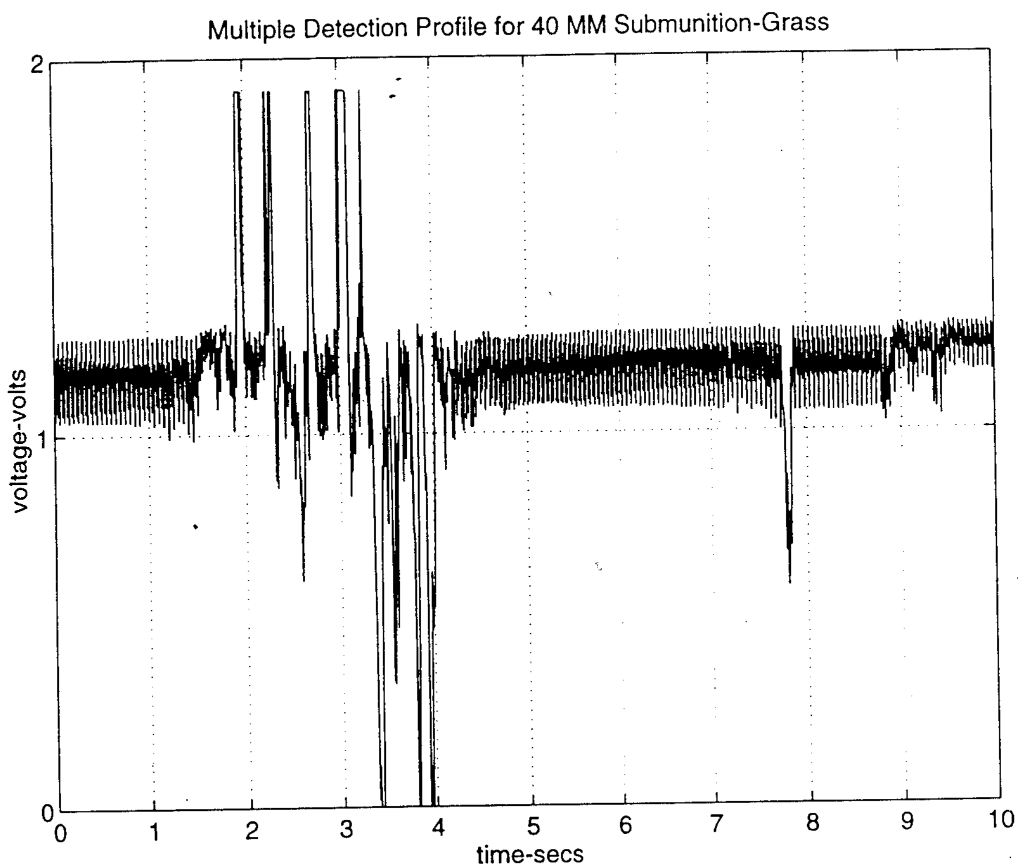


Figure 25. 40 MM Multiple Encounter Signature

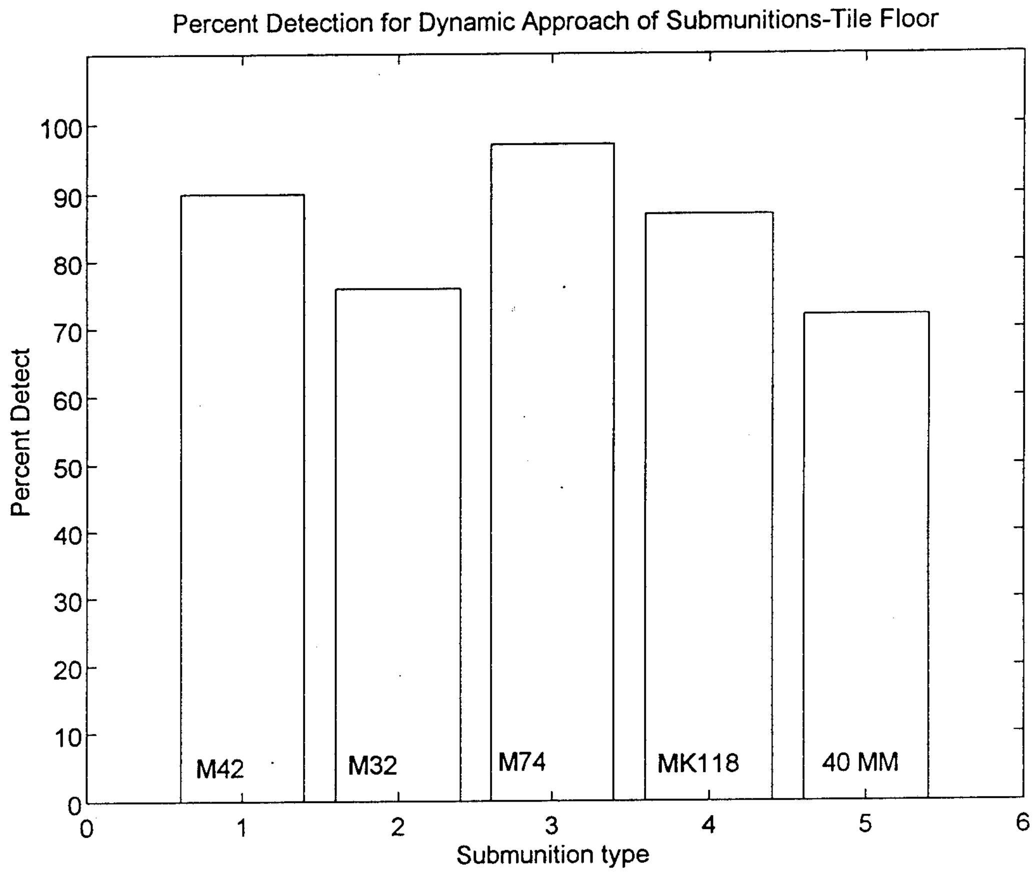


Figure 26. Laboratory Dynamic Probability of Detect Results

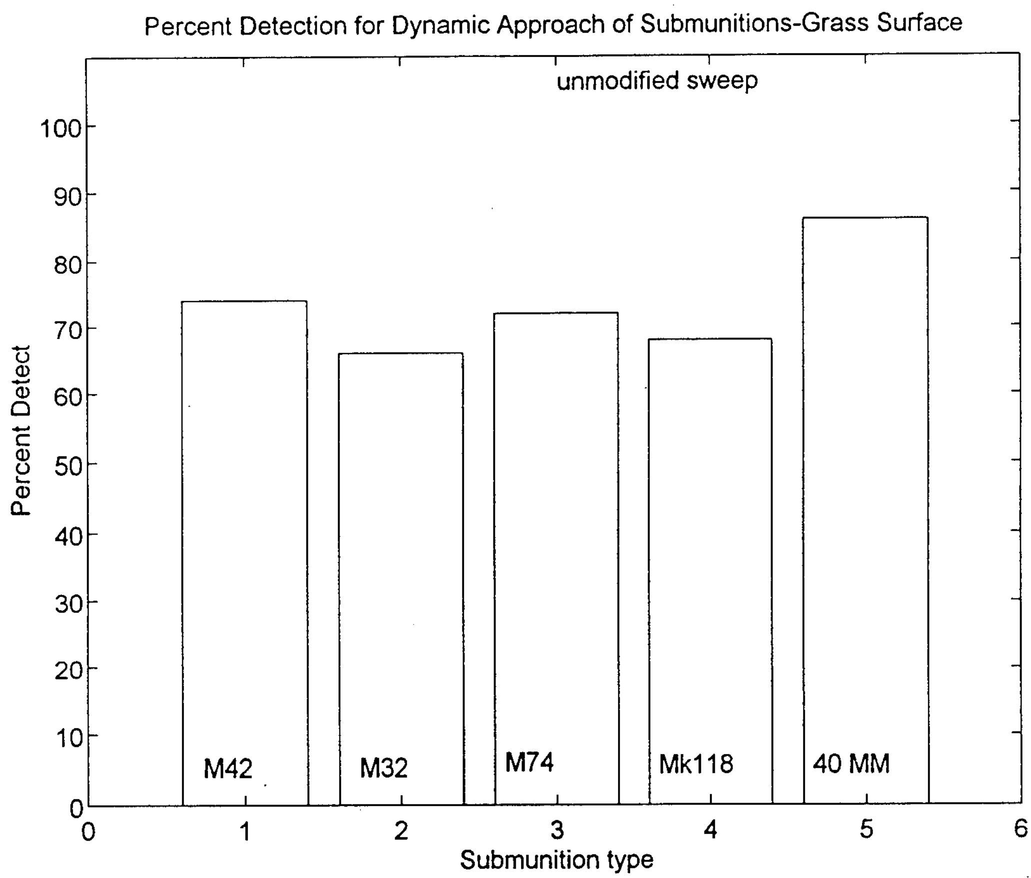


Figure 27. Field Dynamic Probability of Detect Results-
Unmodified Sweep

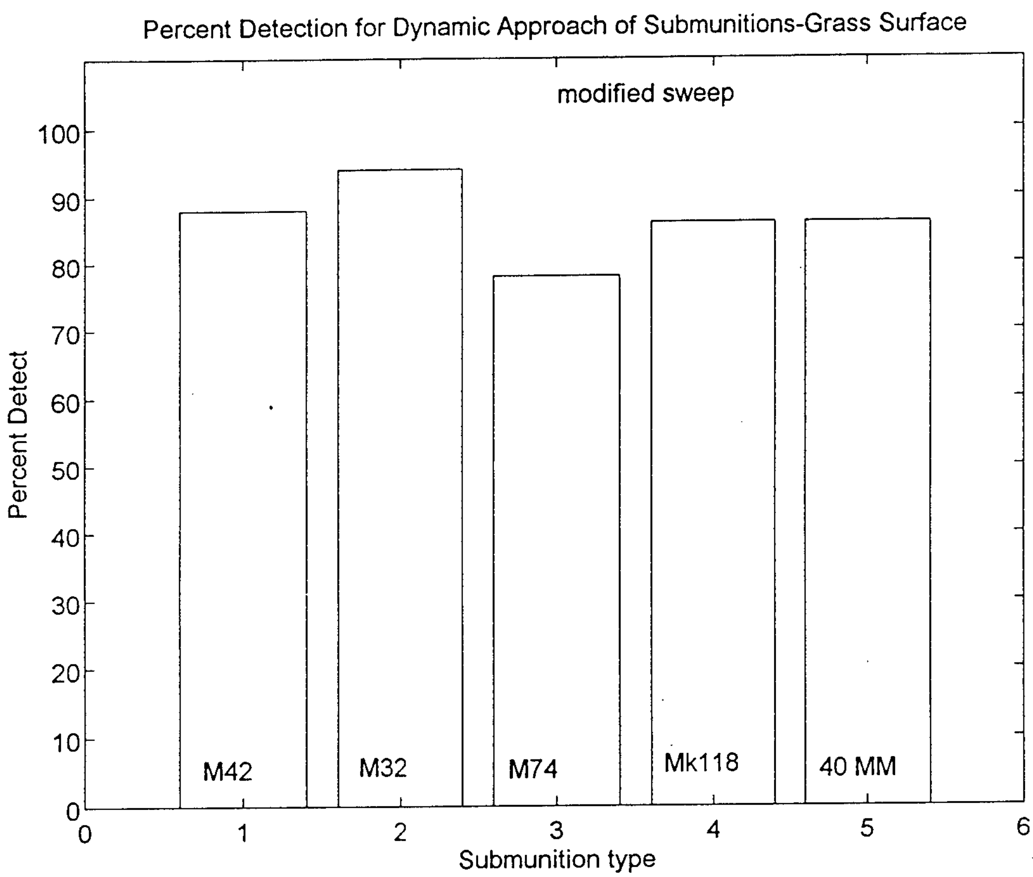


Figure 28. Field Dynamic Probability of Detect Results-
Modified Sweep

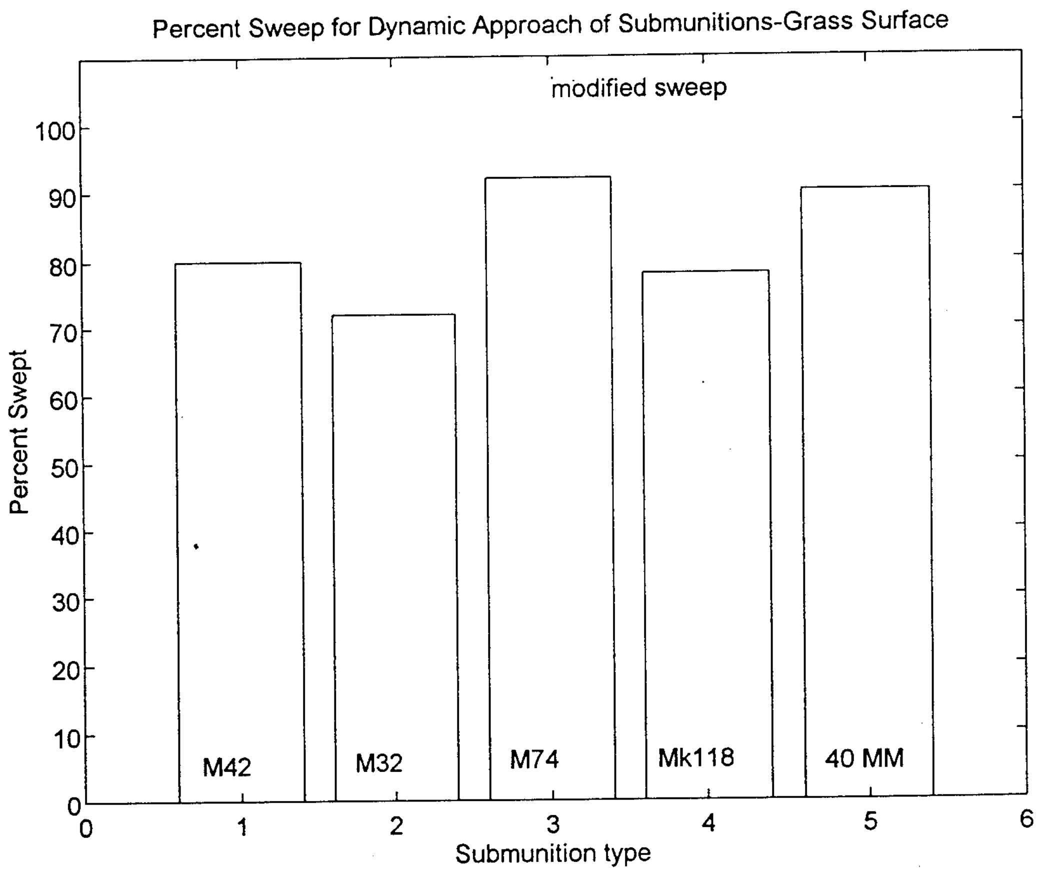
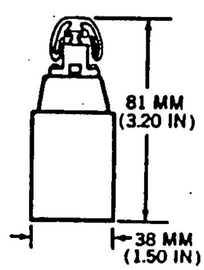


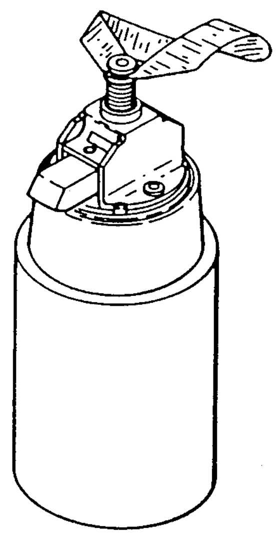
Figure 29. Field Dynamic Sweep Results-Modified Sweep

APPENDIX B. GENERAL SUBMUNITION INFORMATION

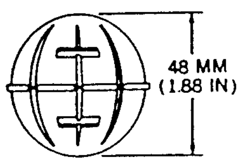
All submunitions used in these tests are inert and of U.S. origin.

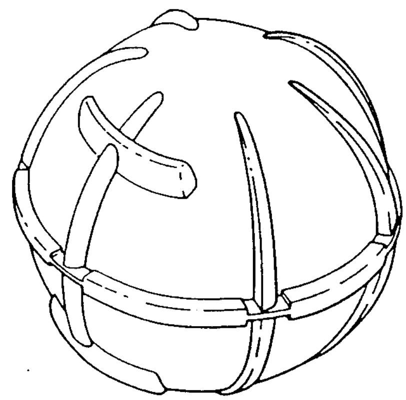
M42 Grenade- A dual-purpose, high explosive munition containing a shape charge and incorporating an impact-inertia fuze. The grenade is stabilized, and armed in flight, by a ribbon stabilizer. They can be delivered by projectiles or rockets. The submunition is very sensitive to movement when armed. The body of the submunition is steel with a copper lined shaped charge container. Live submunition weight is approximately 198 grams. Inert weight as tested-207 grams.
[EODB 60T-2-2-12]



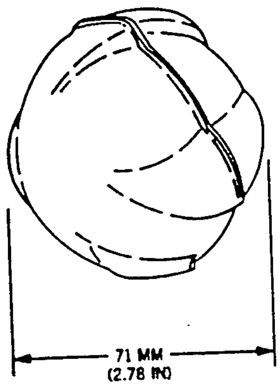


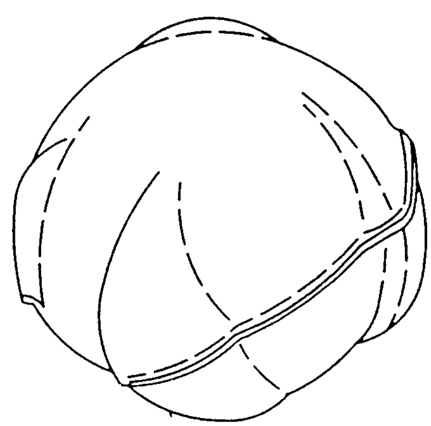
M32 Grenade- Small, multi-purpose, high-explosive munitions which may be delivered by canister (via aircraft) or rocket. They may be fuzed for immediate or random-delay detonation. Arming is accomplished via centripetal acceleration of the submunition in the airstream, following dispersal from delivery container. The body of the submunition is composed of two aluminum hemispheres and a steel clamp ring which holds them together. Live weight is approximately 136 grams. Inert weight as tested-122 grams [EODB 60T-2-2-26]



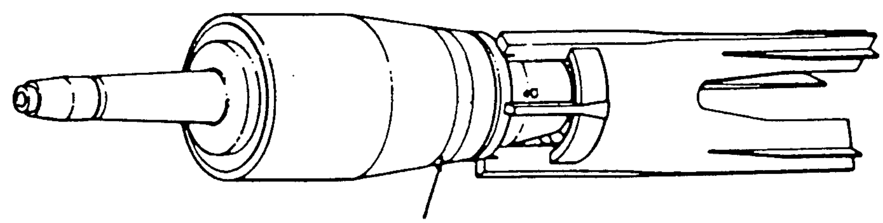


M74 Grenade-Small, multi-purpose, high-explosive munitions which may be delivered via missile. They may be fuzed for immediate or random-delay detonation. Arming is accomplished via centripetal acceleration of the submunition in the airstream, following dispersal from delivery container. The body of the submunition is composed of two high density tungsten, nickel and iron alloy hemispheres housed in steel overlay shells, This results in a very heavy submunition for the size. Live weight is approximately 590 grams. Inert weight as tested-581 grams.
[EODB 60T-2-2-28]

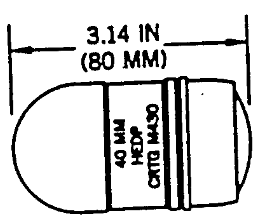


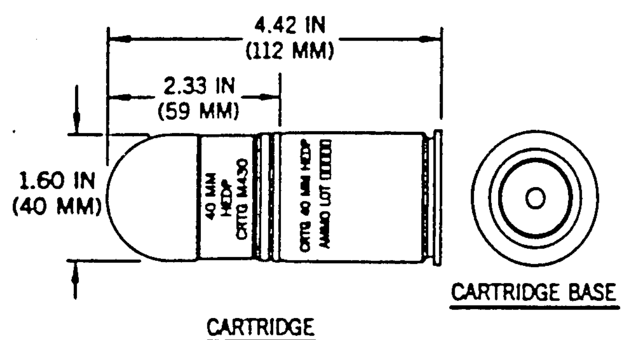


Mk 118 Bomb- Small high explosive bomblets containing shape charges, which are launched from cannisters, for use against tanks. They are fin-stabilized (fins were not present during thesis research as they are often lost following impact) and are initiated upon impact. The bomblet body is steel. Each live bomblet weighs approximately 590 grams. Inert weight as tested-517 grams.
[EODB 60T-2-2-6]



40 MM HE Projectile- Percussion-fired, high-explosive, dual-purpose fragmentation cartridges with a shaped charge effect option. The projectile is centripetally and set-back armed with a graze sensitive fuze. The body of the projectile is steel with a copper shape charge liner and rotating band. It has a weight of 340 grams. Inert weight as tested-236 grams.
[EODB 60D-2-2-23-10]

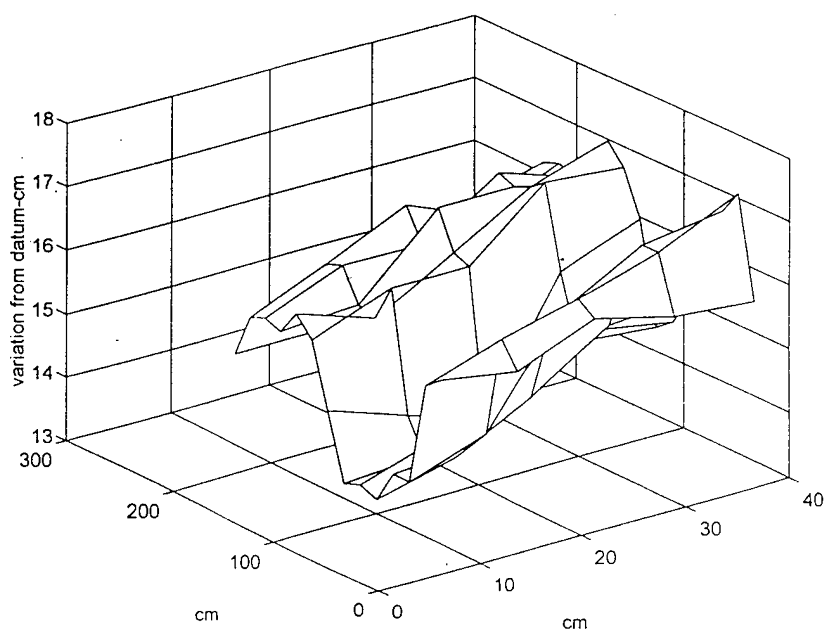




APPENDIX C. OUTDOOR TEST SURFACE DATA

All outdoor testing was conducted on a section of lawn located at the Naval Post Graduate School, Monterey, CA. The area used consisted of a 2.5 meter by .33 meter section of bermuda grass growing on a base of sand and loam. The test section was bounded on its long sides by wooden boards suspended approximately 5 cm above the grass surface by stakes.

The area chosen was slightly sloped to one side and was fairly irregular along its surface, exhibiting patches of bare ground and clumps of grass. The plot below is intended to provide some idea of the surface irregularity. It is based upon seventy evenly spaced measurements of ground level from a constant datum taken over the test area. The maximum variation in ground level between any two points was 3.8 cm with a maximum slope between points of 14.7 degrees in the transverse and 8.6 degrees in the longitudinal direction.



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